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Abstract

A model advanced turbofan was acoustically tested in the NASA Glenn 9- by 15-Foot-Low-Speed Wind Tunnel (LSWT), and in two other aeroacoustic facilities. The Universal Propulsion Simulator (UPS) fan was designed and manufactured by the General Electric Aircraft Engines (GEAE) Company, and featured active core, as well as bypass, flow paths. The reference test configurations were with the metal, M4, rotor with hardwall and treated bypass flow ducts. The UPS fan was tested within an airflow at a Mach number of 0.20 (limited flow data were also acquired at a Mach number of 0.25) which is representative of aircraft takeoff and approach conditions. Comparisons were made between data acquired within the airflow (9×15 LSWT and German-Dutch Wind Tunnel (DNW)) and outside of a free jet (Boeing Low Speed Aero acoustic Facility (LSAF) and DNW). Sideline data were acquired on an 89-in. (nominal 4 fan diameters) sideline using the same microphone assembly and holder in the 9×15 LSWT and DNW facilities. These data showed good agreement for similar UPS operating conditions and configurations. Distortion of fan spectra tonal content through a free jet shear layer was documented, suggesting that in-flow acoustic measurements are required for comprehensive fan noise diagnostics. However, there was good agreement for overall sound power level (PWL) fan noise measurements made both within and outside of the test facility airflow.

Introduction

The Universal Propulsion Simulator (UPS) fan was designed and built by General Electric Aircraft Engines (GEAE) to explore advanced fan stage concepts for future quiet turbofan engines. The fan stage was tested in the NASA Glenn 9- by 15-Foot-Low Speed Wind Tunnel (LSWT) using several rotor designs. These acoustic tests explored the fan performance with unswept, forward-swept, and aft-swept rotors of both metal and composite construction. The fan stage was tested with, and without acoustic treatment on the outer wall of the bypass flow duct.

The UPS fan was also tested in the Boeing Low Speed Aero acoustic Facility (LSAF) free jet, and in the German-Dutch Wind Tunnel (DNW) free jet facility using the baseline “M4” rotor with and without bypass duct acoustic treatment. Tests in the DNW and 9×15 facilities were performed in air flowing at a Mach number of 0.20; while the LSAF tests were conducted with a free jet flow at Mach numbers of 0.20 and 0.25. These airflows are representative of aircraft takeoff and approach conditions.

Acoustic test results from these three facilities provided a unique opportunity to compare and quantify data quality and acquisition techniques for far field acoustic data acquired both within the flow field (NASA 9×15; DNW inflow acoustic surveys), and outside of a free jet shear layer (Boeing LSAF and DNW out of flow surveys).

Reference 1 is a GEAE report comparing acoustic results for the UPS fan in these three facilities from the perspective of evaluating the 9×15 LSWT data quality relative to that obtained in the LSAF and DNW facilities. Toward that end, Reference 1 concludes that the 9×15 LSWT is a “viable test facility for quiet, high-bypass ratio, model-fan-rig, acoustic testing.” The current report, based on NASA evaluation of the data, confirms this conclusion and also explores aspects of the UPS acoustic data beyond what was presented in Reference 1.

Description of Test

Research Fan

The UPS fan is representative of future, high bypass ratio turbofan engines. Figure 1 is a cross-sectional sketch of the UPS fan. The bypass rotor diameter is 22.0 in. The bypass rotor-vane ratio is adequate to achieve cutoff of the fundamental interaction tone (Refs. 2 and 3). The UPS fan has an active core (or booster) stage which includes a powered rotor (same rotational speed as the bypass fan) with inlet and outlet stators. The core flow passage also has deswirl struts slightly downstream of the core outlet guide vanes, and aft load struts somewhat further downstream. The core passage also has a full passage screen to adjust flow rates, and subsequently stage bypass ratio. Table 1 is a listing of the fan design parameters.

UPS fan stage results presented herein are for the M4 unswept metal rotor. Additional acoustic tests performed in the 9×15 LSWT allowed investigation of rotor forward and aft sweep effects, and relative performance of composite versus metal blade construction (Ref. 4). The rotor was powered by a high pressure air turbine drive (Ref. 5) with the drive air and instrumentation supplied through a support strut mounted on the test facility floor.

The acoustic results reported herein are for the UPS bypass fan stage with either hard or acoustically treated walls. Figure 1 shows the presence of acoustic treatment in the inlet and bypass ducts. The acoustic treatment was always present on the inner wall of the bypass duct upstream and downstream of the bypass stator. The inlet and outer wall bypass duct treatment panels were removable and could be replaced with hard-wall panels. However for the tests reported here, the acoustic treatment was always present on the outer bypass duct wall between the rotor and the stator. Letter designations are used in this report to distinguish between different configurations of hard wall and treated wall panels in the inlet and the outlet section of the bypass duct. The letter “H” designates a hard-wall panel and the letter “T” designates a treated panel. Thus, the hard-wall configuration is designated “HTH” and the completely treated configuration is designated “TTT.”

Test Facilities and Acoustic Instrumentation

The UPS fan was tested in three “world class” aeroacoustic facilities. These facilities included the 9×15 LSWT, the Boeing free-jet facility (LSAF), and the German-Dutch large free-jet facility, (DNW). Testing in these three facilities provided comparative acoustic results for the M4 unswept metal rotor with hard-wall (HTH) and two treated bypass duct configurations. These tests also afforded an opportunity to compare relative merits of taking fan acoustic data within an airflow (9×15 LSWT and DNW) and outside of a free jet (LSAF and DNW).

NASA Glenn 9×15 LSWT

The 9×15 LSWT is located in the low speed return leg of the 8×6 Supersonic Wind Tunnel (Fig. 2). The tunnel test section walls, floor and ceiling had acoustic treatment to produce an anechoic test environment (Refs. 6 to 8). Figure 3 is a sketch of the test fan installed in the 9×15 LSWT. Sideline acoustic data were acquired with a computer-controlled translating microphone probe (also seen in the photograph of Figure 4) and with an array of fixed microphones mounted on the tunnel wall. The translating microphone probe acquired data at 48 sideline geometric angles from 29° to 138° relative to the fan inlet highlight. The translating probe traverse was at 89 in. from the fan rotational axis (approximately four fan diameters). The acoustic data were acquired through a digital computer system and stored for post-run analysis. Acoustic data were acquired in a Mach number 0.20 flow, which is representative of takeoff and approach conditions and provides flight acoustic conditions (Ref. 9).

Constant bandwidth spectra were acquired in the 9×15 LSWT at 6 and 118 Hz bandwidths at each translating probe position. These constant bandwidth spectra were electronically merged and used to generate 1/3rd octave spectra. The 9×15 LSWT results presented herein are in terms of both constant bandwidth and 1/3rd octave spectra. The survey data were instrument corrected and corrected for atmospheric attenuation using Doppler-shifted frequencies over the propagation path (lossless acoustic data). Geometric (observed) sideline angles were converted to emission angles according to the relationship:

$$\Theta_{em} = \Theta_{geom} - \sin^{-1}(M_o \sin \Theta_{geom})$$

where Θ_{em} and Θ_{geom} are, respectively, the emission and observed sideline angles, and M_o is the test section Mach number.

There was initially some concern as to the validity of translating microphone probe survey data as opposed to data acquired with conventional fixed microphones. The fixed wall microphone array was vertically staggered to minimize wake interaction from upstream microphone holders. Acoustic data acquired during the 9×15 LSWT UPS test were used to compare fixed and translating microphone data quality (Ref. 8). Wakes from upstream microphone holders were seen to persist a significant distance downstream, thus possibly compromising data quality from downstream fixed microphones. Also, the vertical stagger used to minimize this wake interaction introduced a new, azimuthal variation in the acquired data—a problem not associated with a single traversing microphone. Otherwise, data quality from both fixed and translating microphones was shown to be equivalent. Acoustic data presented herein are for the translating microphone probe.

Boeing LSAF

The Boeing Low Speed Aeroacoustic Facility (Ref. 10) (LSAF) allows aeroacoustic testing in a free jet environment, rather than within the tunnel flow as provided by the NASA LSWT. Figure 5 shows the mic placement relative to the UPS fan installed in the LSAF. Data were taken with free jet Mach numbers of 0.20 and 0.25. Acoustic data were only acquired outside of the free jet due to free jet size limitations. Data were acquired by Boeing and GEAE. These data were instrument corrected and adjusted for free jet shear layer effects and atmospheric attenuation, and are primarily presented as lossless 1/3rd octave results at corresponding emission angles. Limited constant bandwidth spectra were also acquired; however these data were not provided with absolute noise levels.

German-Dutch Wind Tunnel DNW

The DNW is a large free-jet facility (Refs. 11 to 13) which permits acoustic data acquisition both within the free jet (as for the NASA LSWT) and outside the shear layer (LSAF). Figures 6 and 7 are sketches which show the UPS installation in the DNW facility. Acoustic data were acquired by DNW and GEAE personnel and as constant bandwidth (36 Hz) and 1/3rd octave spectra. Acoustic data were acquired at three sidelines distances:

- Fixed microphones outside of the free jet on a 36 ft sideline.
- Within the free jet on a 120-in. sideline using the DNW translating microphone assembly.
- Within the free jet on an 88-in. sideline using the same holder and microphone as was used for the NASA 9×15 UPS tests.

The acoustic data were likewise instrument corrected and adjusted for atmospheric attenuation. Data for the 36 ft sideline were also corrected for the free jet shear layer. The DNW data are presented in terms of sideline emission angles relative to the UPS inlet highlight.

Results and Discussion

Aerodynamic Performance

NASA 9×15 LSWT Results

Limited aerodynamic results are available for the UPS tests in the 9×15 LSWT. Data were taken at a tunnel Mach number of 0.20 over a range of fan speeds from 7400 to 14000 corrected revolutions per minute (rpm) (see Table 2). The fan design speed (Table 1) was 12647 rpm for the baseline (M4) rotor.

The UPS fan was tested in the 9×15 LSWT with the baseline rotor with and without bypass duct acoustic treatment. Acoustic treatment was always present on the inner flow surface of the bypass duct (see Fig. 1). Data were taken with acoustic treatment on the outer surface of the bypass duct and without acoustic treatment on the outer surface.

A representative aerodynamic fan map of pressure ratio versus bypass corrected weight flow is shown in Figure 8. These results are for the UPS tests in the 9×15 LSWT for the M4 rotor in the hardwall and acoustic duct treatment configurations. These results show little change in performance between these three configurations.

Acoustic Performance

NASA 9×15 LSWT Results

Effective Perceived Noise

The effective perceived noise level (EPNL) provides a subjective measure of the aircraft flyover noise levels. This value is derived from the flyover sound pressure level profiles and is a function of frequency, duration, and tone content. Effective perceived noise levels were calculated by GEAE for a 1000-ft. flyover using the 9×15 LSWT results. Assumptions were made in generating the noise profiles since the stipulated 10 dB sideline noise reduction from peak levels was typically not captured by the tunnel acoustic instrumentation for aft angles. A scale factor of 5.6 was used. EPNL values are calculated from “full-scale engine” sound pressure data up to 10 kHz. Thus model acoustic data up to about 60 kHz were utilized with this scale factor. Figure 9 compares EPNL levels for the baseline M4 rotor at 0° fan axis angle-of-attack. Results are shown for the hard-wall (HTH) and treated (TTT) bypass duct configurations.

Sideline Acoustic Results

Figure 10 shows the nominal core and bypass blade-vane interaction frequencies as a function of fan speed. This figure is included to assist in identifying tone orders in subsequent acoustic spectra.

Figure 11 shows constant bandwidth (6 Hz) spectra for the M4 rotor at a 74° sideline emission angle at 12 k corrected rpm (rpm_c). There is significant multiple pure tone (MPT) content for the results for the hardwall (HTH) configuration in Figure 11. The spectrum with duct acoustic treatment (TTT) in place shows the treatment effectiveness in reducing these MPT levels at this upstream sideline location.

Figure 12 presents selected sideline 1/3rd octave band directivities for the two test configurations. Results are shown for a subsonic rotor tip speed (8.2 k rpm_c) and a transonic speed (12 k rpm_c). The broadband noise results at 8 kHz and 8.2 k rpm_c (Fig. 12(a)) show noise levels for the hard-wall configuration (HTH) to be highest at the downstream sideline angles. Duct acoustic treatment (TTT) reduced noise levels at all measured sideline angles. Similar results are seen for the bypass 3 BPF tone (Fig. 12(b)). There is considerable MPT content in the noise spectra at 12 k rpm_c (Figs. 12(c) to (e)) at forward emission angles, showing the effectiveness of the acoustic treatment for reducing MPT levels.

Boeing LSAF Results

The UPS fan was tested in the Boeing LSAF free-jet facility. Far field microphones were located outside of the free jet as shown in Figure 5. Acoustic UPS data provided by GEAE to NASA were for the M4 metal rotor in the HTH, HTT, and TTT configurations. (The HTT configuration was with a hard-wall inlet duct, and acoustic treatment between the bypass rotor and stator as well as downstream of the fan stage.) Table 3 lists the LSAF data points available for this analysis. These data come from two separate LSAF entries. The first data set, designated “Entry 2” had the far field microphone array at a 6.1-m (20-ft) distance from the model centerline in the aft direction and on a 6.1-m (20-ft) radius in the upstream direction as illustrated in Figure 5. For this entry data were taken for the UPS model within the free jet at velocities with Mach numbers of 0.20 and 0.25. The second data entry, “Entry 3,” had a free jet velocity with Mach number 0.20 and microphones that were located in a similar pattern with radius and sideline distances of 4.6-m (15-ft).

LSAF and 9×15 LSWT Directivities

Figures 13 to 24 compare $1/3^{\text{rd}}$ octave directivities from LSAF with comparable 9×15 LSWT results. In particular, these figures compare the relative effectiveness of the bypass duct acoustic treatment for the UPS fan as installed in these two facilities. A second objective is to validate the relatively close (4 fan diameter) sideline used in the NASA 9×15 LSWT to obtain far field data. The concern is that noise radiates from both the fan inlet and exhaust, and noise data taken too close to the model will not show true far field directivities. The LSAF data were adjusted to an 88-in. sideline for comparison with the 9×15 LSWT data.

Figure 13 shows $1/3^{\text{rd}}$ octave directivities at 8.2 k rpm_c and 5 kHz (spectral broadband region). Data are shown comparing the TTT and HTH results from the 9×15 LSWT with similar results from the two LSAF entries. A directivity curve at windmill condition is included in the 9×15 LSWT comparisons to show that fan noise data, even at this low fan speed, is above tunnel background noise levels. The general trend is that the acoustic liner was somewhat more effective in the LSAF tests than what was observed for the 9×15 LSWT tests. The reason for this difference is unknown, but may relate to slight differences in the fan build (segment alignment, seals, etc.) for the two tests. The data trends are similar between the 9×15 LSWT and LSAF Entry 2 data—in both instances the liners were much more effective at aft sideline angles. The LSAF Entry 2 data also compares noise levels for the HTH configuration with both free jet flows with Mach numbers 0.20 and 0.25, showing that there is essentially no difference in measured fan noise levels for these two flows. The LSAF Entry 3 data shows a comparison between TTT and HTT configurations, with the expected result that aft sideline noise levels (aft treatment for both curves) are identical.

Figure 14 presents directivity results for the same fan speed at 8 kHz (broadband). These results also show the acoustic liner to have better performance in the LSAF tests than for the 9×15 LSWT tests.

Figures 15 and 16 show directivities at 10 k rpm_c. Again, liner performance is somewhat better in the LSAF. Results for the 9×15 LSWT at 6300 Hz (broadband) and 8 kHz (bypass 2BPF/core BPF) suggest that the liner was effective in removing both tone and broadband noise.

Liner performance in the 9×15 LSWT was quite good at fan speeds with significant MPT spectral content. Figures 17 and 18 show directivities at 11 k rpm_c. MPT content begins to appear in the constant bandwidth spectra at this fan speed. At 4 kHz (Fig. 17, MPT and bypass BPF tones) the liner significantly reduced noise levels for sideline angles downstream greater than about 55°. A second trend—evident in these directivity comparisons, is for higher noise levels associated with the liner at upstream angles from 30° to 55°. The reason for these high liner-associated levels is unclear, but may be due to inflow disturbances associated with the presence of the liner. Another unexplained result is the difference in aft noise levels for the LSAF Entry 3 results where both configurations (TTT and HTT) had aft duct treatment.

Figure 18 compares directivities for 11 k rpm_c at 8 kHz, which contain MPT, bypass 2BPF and core BPF tones. Again, inlet acoustic liner effectiveness was greater in LSAF than in the 9×15 LSWT. The high noise levels observed for the acoustic liner at 4 kHz (Fig. 17) near 45° sideline emission angle are not seen at this higher frequency.

Figures 19 to 21 show directivity comparisons at 12 k rpm_c, which is the speed region of maximum MPT content. Figure 19 shows broadband results at 4 kHz. (Only TTT data were available for the LSAF Entry 2.) MPT generation in both facilities is significant at this speed and the liner is apparently quite effective for removing these tones. The downstream noise level difference between the TTT and HTT configurations for the LSAF Entry 3 data is significant in Figure 19. This trend (which persists throughout the 12 k rpm_c comparison between the 9×15 LSWT and the LSAF directivities) continually shows relatively higher aft noise levels for the HTT configurations. The reason for this difference in what should be comparable (same duct treatment) data is unknown. It is possible that something changed on the aft liner for the HTT configuration and that this suggested change degraded the acoustic environment of the UPS fan for subsequent higher fan speeds with this configuration.

Figure 20 shows results for 5000 Hz, which contain the bypass BPF tone which is now cut-on. The liner effectiveness is especially good for the LSAF Entry 3 results (LSAF HTH results for Entry 2 were not available). The 9×15 LSWT results show a higher upstream noise level associated with the liner similar to what was observed at 11 k rpm_c and 4000 Hz (Fig. 17). The directivity comparisons at 8 kHz (Bypass 2BPF, Fig. 21) again show somewhat better liner performance in the LSAF.

Figures 22 to 24 show directivity results at 13 k rpm_c, where all rotor-stator interaction tones are firmly cut-on. Multiple pure tones are also present in the spectra. Figure 22 shows results for the broadband at 4 kHz, while Figures 23 and 24 show, respectively, the bypass BPF tone at 5 kHz, and the bypass 2BPF and core BPF tones at 10 kHz. The comparisons at 4 kHz (broadband) again show the liner to be much more effective in the LSAF than in the 9×15 LSWT. However, there is still a significant difference in liner performance for the two LSAF entries, with Entry 3 results showing the high downstream noise levels associated with the HTT configuration.

The 9×15 LSWT TTT and HTH comparisons in Figures 22 to 24 show the liner to only be effective in the downstream region, while the liner continues to be effective throughout the sideline survey for the two LSAF entries.

Shear Layer Tone Distortion

Fan tones originating from blade row interaction and MPTs are often distorted through a free jet shear layer, with this effect becoming more pronounced at higher frequencies. This effect is explored for the comparisons between the 9×15 LSWT and the LSAF data of selected constant bandwidth spectra in Figures 25 to 30. Spectra for both the 9×15 LSWT data and LSAF data have a 6 Hz bandwidth. A limited selection of constant bandwidth spectra for the UPS LSAF entries was available to NASA. The absolute calibration of these spectra was unavailable.

Figure 25 compares UPS M4 HTH data acquired within an airflow with Mach number 0.20 (9×15 LSWT) with data acquired outside a free jet with Mach number 0.25 (LSAF). The fan is operating at 8.2 k rpm_c and the data are for a sideline emission angle of 130°. Highly-defined pure tones which are present in the wind tunnel data are poorly defined in spectra acquired outside of the free jet due to shear layer diffraction.

This effect is even more dramatic at 11 k rpm_c and a 75° emission angle where the spectra have significant MPT content (Fig. 26). Figures 27 and 28 show the shear layer diffraction effects at 12 k rpm_c and sideline emission angles of 50° and 75°, respectively. Tones occurring at frequencies below about 4 kHz are fairly well represented outside of the free jet shear layer.

The UPS fan showed reduced MPT generation with the rotor well into supersonic tip speed (13 k rpm_c, Figs. 29 and 30). In these comparisons, the tones were only effectively transmitted through the free jet shear layer at frequencies below 2 kHz.

It is important to note that this lack of tone resolution through a free jet shear layer does not seem to affect EPNL calculations, which are based on the acoustic energy along a “flyover” sideline. Thus, free jet data is valid for measurements such as EPNLs, but appears to have limited value for diagnostic fan source analysis.

DNW Results

The German-Dutch Wind Tunnel (DNW) tests of the UPS fan provided a unique opportunity to directly compare data acquired both within and outside of a free jet. Also, data acquired from the DNW tests could be directly compared to the inflow results from the 9×15 LSWT and far field data acquired outside of a shear layer (LSAF). Acoustic data were acquired for the two baseline UPS configurations utilizing the metal M4 rotor and hardwall (HTH) and treated (TTT) bypass flow passages. Acoustic data were acquired in the DNW along a 36-ft sideline outside of the free jet as well as with sideline traverses at 120 and 88 in. within the free jet (Figs. 6 and 7). The closer, 88-in. sideline data were acquired using the exact same microphone holder and microphone assembly as was used to acquire the 9×15 LSWT data, making these comparisons especially valid. All of the DNW data were acquired with a free jet operating at a Mach number of 0.20. Table 4 shows the data points which were acquired for the UPS fan in the DNW facility and subsequently provided to NASA by GEAE. Data were provided as both 1/3rd octave and 36 Hz constant bandwidth spectra.

Effect of Sideline Distance

There continues to be some question as to the minimum acceptable sideline distance for representative fan acoustic data. Data taken in the 9×15 LSWT are physically limited to about a 89-in. sideline. Figure 31 compares data taken in the DNW at two different sideline distances within the free jet. The data were processed by General Electric to a 20-ft sideline using their proprietary software. These data are for the M4 rotor hardwall condition with the fan operating at 10 k rpm_c. Data were taken at a 88-in. sideline using the NASA Glenn streamlined microphone holder, and at a 120-in. sideline using DNW survey apparatus. These results offer a unique opportunity to simultaneously compare noise directivities at two sideline distances without source uncertainties such as fan rebuild and different atmospheric test conditions.

Results for bypass BPF (4 kHz) through 3BPF (12.5 kHz) (Figs. 31(a) to (c)) show good agreement between the two sideline distances. There is a slight upstream directivity shift for the 120-in. sideline at downstream angles. This is a geometric error caused by using the inlet highlight as the 90° reference for noise which radiates from the fan exhaust. There is an upstream region of higher noise levels for the 88-in. sideline which was observed at 16 and 25 kHz (Figs. 31(d) and (e)). The reason for this difference is unknown. There is a region of lower noise around 90° for the closer, 88-in. sideline at 40 kHz (Fig. 31(f)) which may relate to more separation of the forward and aft radiation patterns at this closer spacing. The results of Figure 31 show that data taken at the closer 89-in. sideline in the 9×15 LSWT are reasonably representative of fan far field results.

Directivity Comparisons

Figures 32 to 45 present 1/3rd octave directivity comparisons of corresponding 9×15 LSWT and DNW UPS data for the TTT and HTH configurations. The DNW data is for the NASA microphone at an 88-in. sideline. These comparisons tend to be quite good, giving further confidence that valid data may be acquired in either facility.

Figures 32 to 34 compare directivities at 8.2 k rpm_c (8100 rpm_c for the DNW data) for, respectively, the bypass 2BPF and core BPF tone at 6300 Hz, broadband at 10 kHz, and broadband at 20 kHz. The UPS tone directivities (Fig. 32) were somewhat higher for the DNW data. There was close agreement between the 9×15 LSWT and DNW data for broadband at 10 and 20 kHz. The “dip” in the data seen

around 90° is a consequence of the sideline traverse being relatively close (4 fan diameters) with resulting separation of fan forward and aft radiation patterns.

Figures 35 to 38 show directivity comparisons at 10 k rpm_c. UPS operation at 10 k rpm_c provides data which does not contain MPTs, and is therefore not subject to the variable onset of these tones due to specific test flow conditions, etc. Results shown in Figures 35 to 38 are for, respectively, broadband at 4 kHz, bypass 2BPF and core BPF at 8 kHz, bypass 4BPF and core 2BPF at 16 kHz, and bypass 6BPF and core 3BPF at 25 kHz. The agreement between corresponding UPS and DNW data is excellent in each instance, although there is a suggestion that the original acoustic liner (TTT) performed slightly better in the DNW at 16 kHz (Fig. 37) through the mid range of the acoustic traverse.

The UPS fan exhibits maximum MPT generation at 12 k rpm_c. Figures 39 to 41 show directivity comparisons at this speed for, respectively, broadband at 4 kHz, bypass 2BPF and core BPF at 10 kHz, and bypass 4BPF and core 2BPF at 20 kHz. Although not as good as for 10 k rpm_c, the agreement between corresponding data is still acceptable. At 4 kHz (Fig. 40) the TTT configuration data shows good agreement between the two facilities. Multiple pure tones are strongly present in the HTH data, showing slightly more generation in the DNW data near a peak emission angle of 60°. Difference in multiple pure tone generation may still be a factor in the small differences between configuration directivities at 10 and 20 kHz.

Figures 42 to 45 show directivity comparisons at the overspeed, 13.5 k rpm_c condition. The fan noise is highly aft dominated at this rotational speed. Directivities are shown in Figures 42 to 45, respectively, for the bypass BPF (strongly cuton) at 5 kHz, broadband at 8 kHz, bypass 2BPF and core BPF at 10 kHz, and bypass 4BPF and core 2BPF at 20 kHz. The data compares favorably through 10 kHz (Figs. 42 to 44). At 20 kHz (Fig. 45) the 9×15 LSWT data is consistently higher than the corresponding DNW data. The reason for this difference is unknown.

Free Jet Shear Layer Effects

The DNW data afforded an excellent opportunity to further investigate the shear layer induced tone diffraction which was noted in the LSAF data. DNW constant bandwidth (36 Hz) data are available for both the 120-in. sideline within the free jet airflow, and out of the flow at a 36-ft sideline. Figures 46 to 48 compare constant bandwidth spectra acquired within and outside of the free jet shear layer for the hardwall (HTH) configuration. Data are shown for 12 k rpm_c at emission angles of 60°, 90°, and 120°. The comparisons are similar to those seen for the 9×15 LSWT/LSAF data, showing significant tone scattering through the freejet shear layer. The strong MPT content at 60° (Fig. 46) is barely evident outside of the free jet, being essentially limited to frequencies below 4 kHz. Rotor/stator interaction tones which are readily seen in the in flow spectra at 90° and 120° are barely evident in the far field spectra taken outside of the free jet (Figs. 47 and 48). These comparisons again illustrate the difficulty in using fan data taken outside of a free jet to gain insights into fan noise generation mechanisms.

Acoustic Sideline Distance

As was previously mentioned, there is some question concerning the minimum acoustic sideline data required to obtain valid far field measurements. Again, the DNW test provided an insight with in flow sideline data at the nominal 9×15 LSWT distance of 89-in. and also in flow sideline data at a somewhat greater 120-in. The out of flow data at 36 ft is clearly in the far field, but may be compromised by shear layer effects.

Figures 49 to 54 show constant bandwidth (36 Hz) directivities along these three sidelines for the UPS hardwall HTH configuration at 12 k rpm_c. Directivities are shown for the first 4 bypass tone orders and first 2 core tone orders. The constant bandwidth data are instrument corrected, but not adjusted for atmospheric absorption. The general conclusion from these figures is that directivities for the two in flow sidelines (88- and 120-in.) are essentially similar, giving credibility to the 89-in. sideline used in the 9×15 LSWT. The tone directivities in the far field (through the shear layer) reasonably follows that of the

in flow data for the BPF tone (approximately 4500 Hz, Fig. 49), but is not very descriptive at higher frequencies (tone orders). This result is constant with the previous observation that tonal information is significantly compromised through a Mach number of 0.20 free jet shear layer at frequencies above 4000 Hz.

Comparison of DNW and 9×15 LSWT Directivities

It is desirable to compare the constant bandwidth directivities using the same bandwidth (and acoustic energy content). The sound pressure levels in three adjacent 36 Hz acoustic bands were logarithmically added to effectively obtain an equivalent 118 Hz band SPL for selected DNW UPS 88-in. sideline directivities at 10 k rpm_c. This was done for the TTT and HTH configuration data for the first 4 bypass and 2 core tone orders. These adjusted directivities are compared with corresponding (118 Hz) results from the 9×15 LSWT in Figures 55 and 56.

The hardwall comparisons are presented in Figure 55. The data agreement varies for the various bypass tone orders. The bypass BPF tone (Fig. 55(a)) shows fairly good agreement except for the sideline emission angles around 120°. The DNW sideline survey extended somewhat further downstream than did that of the 9×15 LSWT, more clearly showing the reduction in SPL at further downstream angles (desirable for EPNL calculations).

The directivity agreement for the bypass 2BPF tone (Fig. 55(b)) was not especially good, with the DNW results being nearly 10 dB higher at some angles. Directivity comparisons for the 3 and 4BPF bypass tones (Figs. 55(c) and (d)) were somewhat better.

Interestingly, the directivity comparisons for the first 2 core tone orders (Figs. 55(e) and (f)) were quite good between the two facilities. Unlike the bypass tones, the core tones are mostly aft-radiating. Perhaps this simplifies the acoustic resolution since forward and aft radiation interaction (as for the bypass tones) is not a consideration.

There has been some question as to the origin of the “periodic” nature of the bypass tone directivity as illustrated in the preceding plots. An initial concern was that the treated walls of the 9×15 LSWT were, in reality, reflecting some noise, resulting in a cancellation pattern. The comparisons between the 9×15 LSWT and the DNW are useful in exploring this mechanism, in that the DNW with its open free jet does not have the potential for near wall reflection.

Reference 14 explores an analytical solution for fan tone directivity along a similar sideline distance with consideration of forward and aft tone reinforcement and cancellation effects. Predicted bypass tone directivities presented in Reference 14 show a periodicity similar to that seen for the UPS data, reinforcing the idea that this periodicity is due to interaction between forward and aft radiated fan tones. This analytical result and the directivity comparisons between the 9×15 LSWT and the DNW UPS data show that the acoustically-treated walls of the 9×15 LSWT are not a significant source of reflection contamination of the data.

Figure 56 presents directivity comparisons for these bypass and core tones for the treated, TTT configuration at 10 k rpm_c. Figures 56(a) and (b) shows good agreement between data from the two facilities for the bypass BPF and 2BPF tones. However, at 3BPF and 4BPF (Figs. 56(c) and (d)) the 9×15 LSWT data is consistently higher. This results contrast with those of for the HTH configuration (Figs. 55(c) and (d)) which showed relatively good agreement between results for the two facilities.

There was considerable evidence that the acoustic treatment (TTT) tested in the 9×15 LSWT was somehow not as effective compared to the UPS TTT performance in LSAF. It is possible that installation-induced changes in liner performance are causing with higher bypass 3BPF and 4BPF tone levels in the 9×15 LSWT seen for these comparisons.

The core stage interactions tones for the TTT configuration again showed good agreement between the two facilities (Figs. 56(e) and (f)). These tones are essentially unaffected by the presence of the bypass duct acoustic liner.

Concluding Remarks

A model advanced turbofan was acoustically tested in the 9×15 LSWT, the Boeing Low Speed Aeroacoustic Facility (LSAF) and the German-Dutch Wind Tunnel (DNW). The Universal Propulsion Simulator (UPS) fan was designed and manufactured by the General Electric Aircraft Engines (GEAE) Company, and featured powered core, as well as bypass, flow paths. The reference test configurations were with the unswept baseline “M4” rotor with hardwall and acoustically treated bypass flow ducts. These tests afforded an opportunity to compare relative merits of fan acoustic testing within airflow (9×15 LSWT and DNW) and with acoustic measurements taken outside of a free jet (LSAF and DNW) using common test hardware and operating conditions.

The Boeing LSAF tests were with the fan installed in a free jet and far field noise measurements taken outside of the free jet. The UPS acoustic liner was more effective in the LSAF installation than in the 9×15 LSWT. The reason for this difference is unknown, but may relate to small differences between successive builds of the model in the two facilities. The LSAF results showed significant shear layer diffraction of fan tones measured outside of the shear layer. In particular, a significant amount of the diagnostic fan tonal information may be lost by transmission through a shear layer. However, overall noise levels seem to be essentially the same when measured within the flow (9×15 LSWT) or outside of the flow (LSAF).

The German Dutch DNW results provided an excellent opportunity to compare far field acoustic data taken concurrently both within and outside of a free jet. The free jet in this facility was sufficiently large to allow in flow acoustic sideline measurements as well as simultaneous far field (outside of the shear layer) measurements. The shear layer tone diffraction noted for the LSAF tests was further quantified in the DNW. In-flow measurements were made at the DNW using the same microphone holder assembly that was used for the 9×15 LSWT tests and utilizing the same sideline distance as for the NASA wind tunnel tests. These results showed excellent acoustic agreement between the 9×15 LSWT and DNW tests. An additional result of the DNW tests was to quantify the effect of sideline distance. In-flow sideline data were acquired in the DNW at 88 in. (nominal 9×15 LSWT sideline), 120 in., and outside the free jet at 36 ft. The sideline directivities were slightly influenced by fan inlet/exhaust radiation patterns at closer sidelines and higher frequencies; however, the results generally showed that the 89-in. (nominal 4 fan diameter) sideline employed in the 9×15 LSWT should be adequate to acquire “far field” sideline data.

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TABLE 1.—UPS DESIGN PARAMETERS

Bypass Stage:	
Rotor blades.....	22
Stator vanes	54
Core (booster):	
Inlet guide vanes	90
Rotor blades.....	48
Outlet guide vanes.....	70
Deswirl vanes.....	50
Forward load struts.....	8
Full passage screen	1
Aft load struts	8
Rotor-stator axial spacing (mean rotor chords).....	2.75
Bypass stage:	
Pressure ratio	1.49
Bypass ratio:.....	8.85
Mass flow, kg/sec (lbm/sec):.....	46.3 (102.1)
Rotor diameter, cm (in.).....	55.9 (22.0)
Rotor tip speed, m/sec (ft/sec):	370 (1214)
Acoustic Rating Rotor Tip Speeds, m/sec (ft/sec)	
Approach	216 (710)
Cutback.....	293 (960)
Sideline	351 (1152)

TABLE 2.—ACOUSTIC TEST SPEEDS
[Nominal Values.]

Corrected, rpm	Point of interest	Corrected tip speed m/sec, ft/sec	Tip Mach, Tangential
^a 1330	Windmill	38.9 (127.7)	0.11
7400	Low approach	216.5 (710.3)	0.63
8200	High approach	239.9 (787.1)	0.70
10000	Low cutback	292.6 (959.9)	0.85
11000	High cutback	321.8 (1055.9)	0.94
12000	MPT peak	351.1 (1151.9)	1.02
13000	Low takeoff	380.4 (1247.9)	1.11
13500	High takeoff	395.0 (1295.9)	1.15
14000	Overspeed	409.6 (1343.9)	1.19

^aWindmill speed is approximate, depending on tunnel conditions

TABLE 3.—DATA COMPARISON BETWEEN GRC 9×15 LSWT AND BOEING LSAF
[0° AOA, Except As Noted.]

LSAF entry 2: Mach as shown, 20 ft radius upstream and 20-ft sideline aft.

LSAF entry 3: 15-ft radius upstream and 15-ft sideline aft.

Acoustic Treatment—Treated (T) or Hardwall (H): [Inlet]–[Between Rotors and Stator]–[Exhaust Duct]

Corrected, rpm	9×15 (0.20 Mach)		LSAF entry 2			LSAF entry 3 (0.20 Mach)	
	Acoustic treatment configuration	Data taken	Acoustic treatment configuration	Mach	Data taken	Acoustic treatment configuration	Data taken
Windmill	TTT	Yes	TTT	0.20	Yes ^a	HTT	Yes
7000		N.A.	TTT	0.25	Yes		N.A.
7000		N.A.	HTH	0.20	Yes		N.A.
7400	TTT	Yes	TTT	0.25	Yes	TTT	Yes
7400	HTH	Yes	HTH	0.20	Yes	HTT	Yes
7400		N.A.	HTH	0.25	Yes		N.A.
7400		N.A.	HTH	0.06	Yes		N.A.
8200	TTT	Yes	TTT	0.25	Yes	TTT	Yes
8200	HTH	Yes	HTH	0.20	Yes	HTT	Yes
8200		N.A.	HTH	0.25	Yes		N.A.
10000	TTT	Yes	TTT	0.25	Yes	TTT	Yes
10000	HTH	Yes	HTH	0.20	Yes	HTT	Yes
11000	TTT	Yes	TTT	0.25	Yes	TTT	Yes
11000	HTH	Yes	HTH	0.25	Yes	HTT	Yes
11700		N.A.	HTH	0.25	Yes	TTT	Yes
11700		N.A.			N.A.	HTT	Yes
12000	TTT	Yes	TTT	0.25	Yes	TTT	Yes
12000	HTH	Yes			N.A.	HTT	Yes
13000	TTT	Yes	TTT	0.25	Yes	TTT	Yes
13000	HTH	Yes	HTH	0.25	Yes	HTT	Yes
13500	TTT	Yes			N.A.	TTT	Yes ^b
13500	HTH	Yes			N.A.	HTT	Yes ^c
14300		N.A.	TTT	0.25	Yes		N.A.
14300		N.A.	HTH	0.25	Yes		N.A.

^aWindmill data, 3° Angle-of-Attack.

^bAngle-of-Attack is really 3.86°

^cSlight loss of hardwall taping, therefore questionable data

TABLE 4.—GE UPS DATA TAKEN IN THE DNW FREE JET FACILITY
[M4 Rotor, Free jet with Mach Number 0.20.]

Corrected, rpm	Hardwall (HTH)	Treated (TTT)
Windmill	-----	-----
6700	D1/3 rd	D1/3 rd
7300	N1/3 rd , D1/3 rd , SL4	N1/3 rd , D1/3 rd , SL4
8100	N1/3 rd , D1/3 rd , SL2, SL4	N1/3 rd , D1/3 rd , SL2, SL4
10000	N1/3 rd , D1/3 rd , SL2, SL4	N1/3 rd , D1/3 rd , SL2, SL4
10800	N1/3 rd , D1/3 rd , SL2, SL3, SL4	N1/3 rd , D1/3 rd , SL4
12000	N1/3 rd , D1/3 rd , SL2, SL4	N1/3 rd , D1/3 rd , SL2, SL4
13000	N1/3 rd , D1/3 rd , SL2, SL4	N1/3 rd , D1/3 rd , SL2, SL4
13500	N1/3 rd , D1/3 rd , SL3, SL4	N1/3 rd , D1/3 rd , SL4
13900	D1/3 rd	D1/3 rd

Available data:

N1/3rd—1/3rd octave taken with the NASA mike in flow at an 88-in. sideline

D1/3rd—1/3rd octave taken with the DNW in flow translating mic at a 120-in. sideline

SL2—36 Hz narrowband data taken with the DNW translating probe, middle mic

SL3—36 Hz narrowband data taken with the DNW translating probe, lower mic

SL4—36 Hz narrowband data taken with the NASA inflow microphone probe

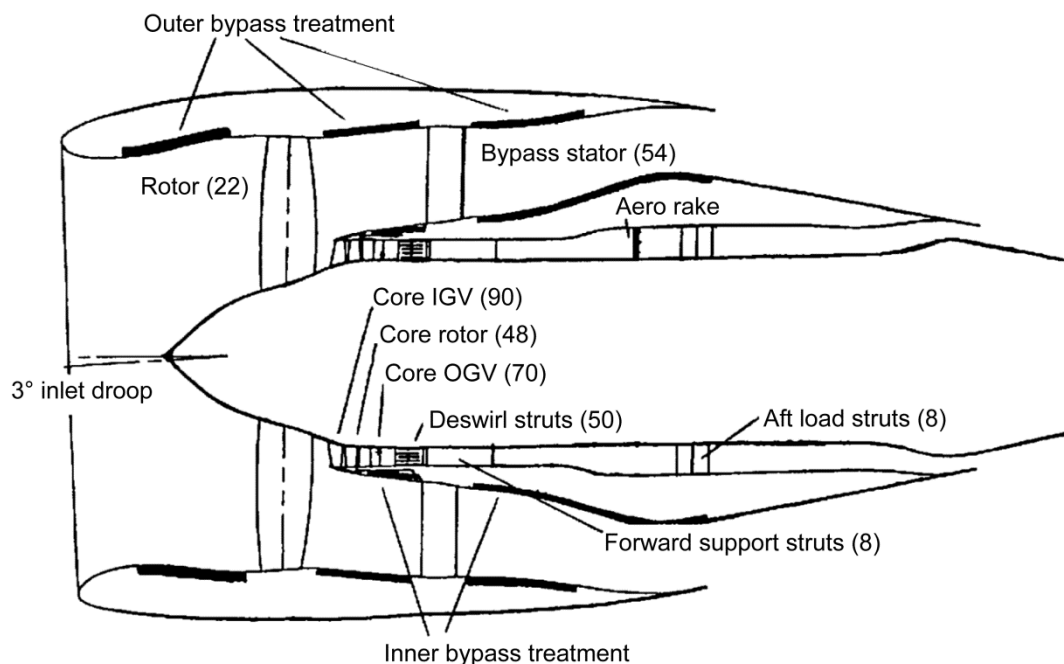


Figure 1.—Cross-sectional view of the UPS fan stage.

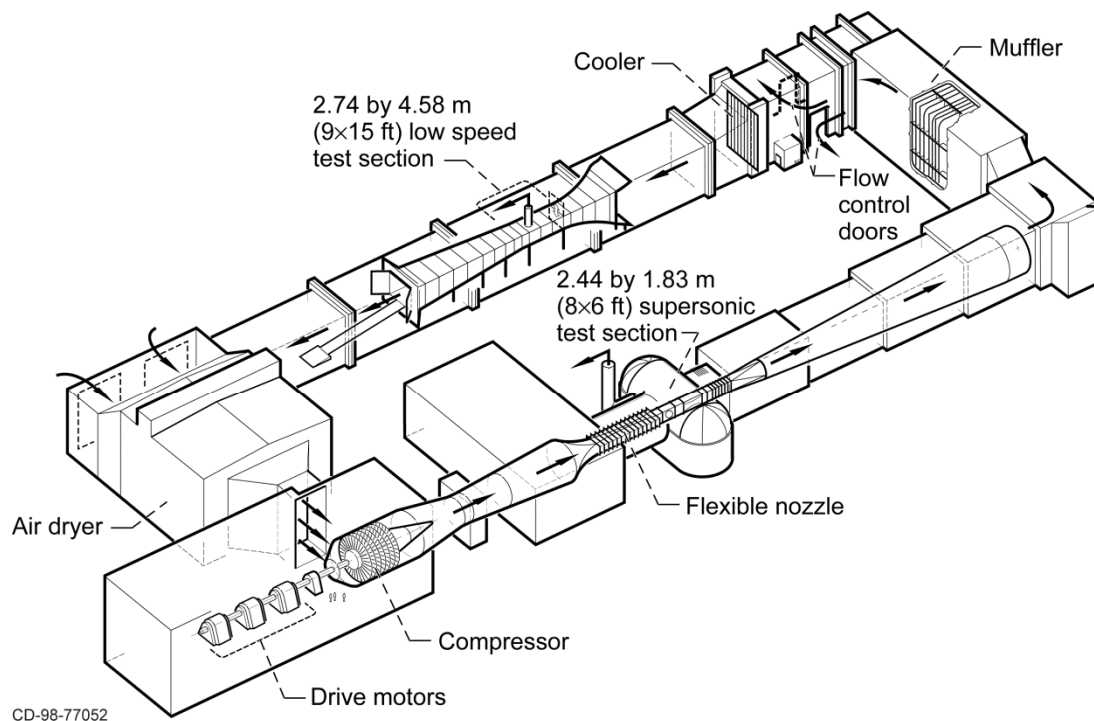


Figure 2.—Sketch of NASA Glenn 9×15 LSWT complex.

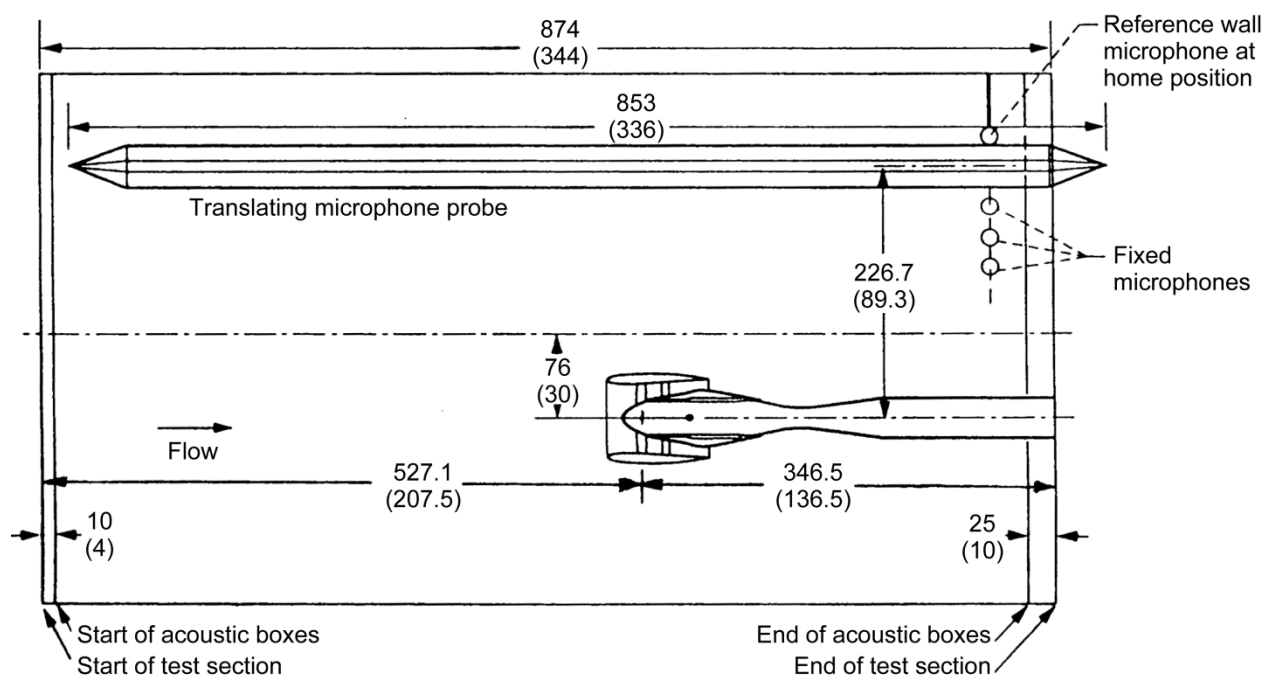


Figure 3.—Sketch of the UPS model installed in the NASA Glenn 9×15 LSWT (dimensions are cm (in.)).

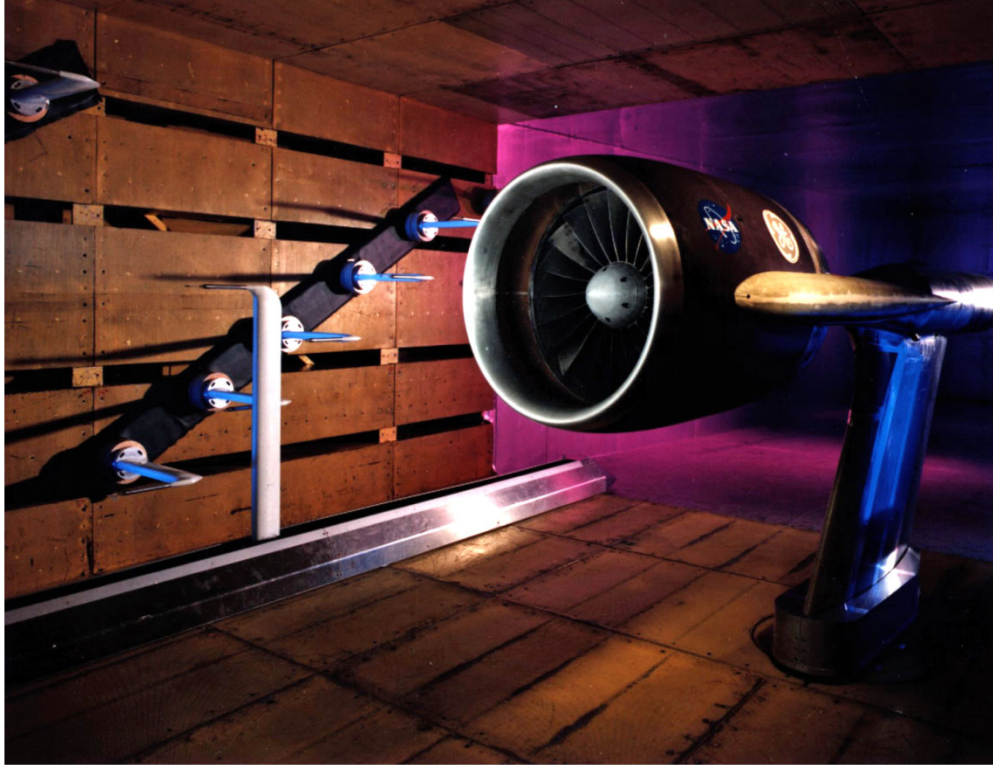


Figure 4.—Photograph of the UPS model installed in the NASA Glenn 9x15 LSWT.

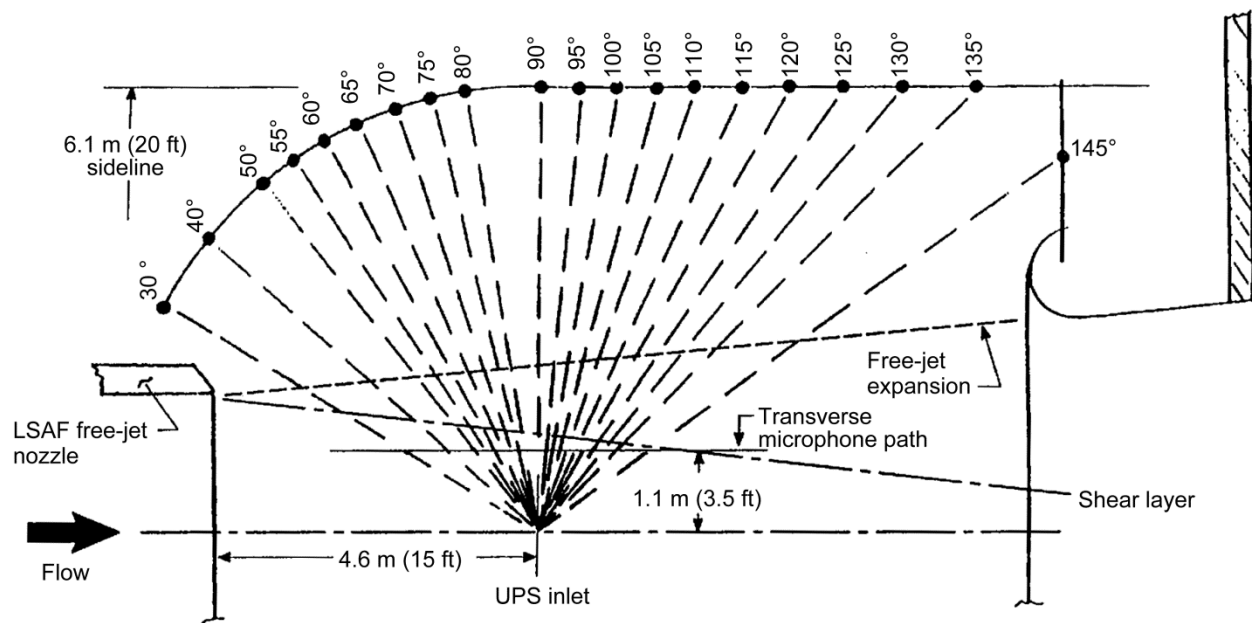


Figure 5.—Microphone placement for the UPS model installed in the Boeing LSAF (Entry 2 configuration).

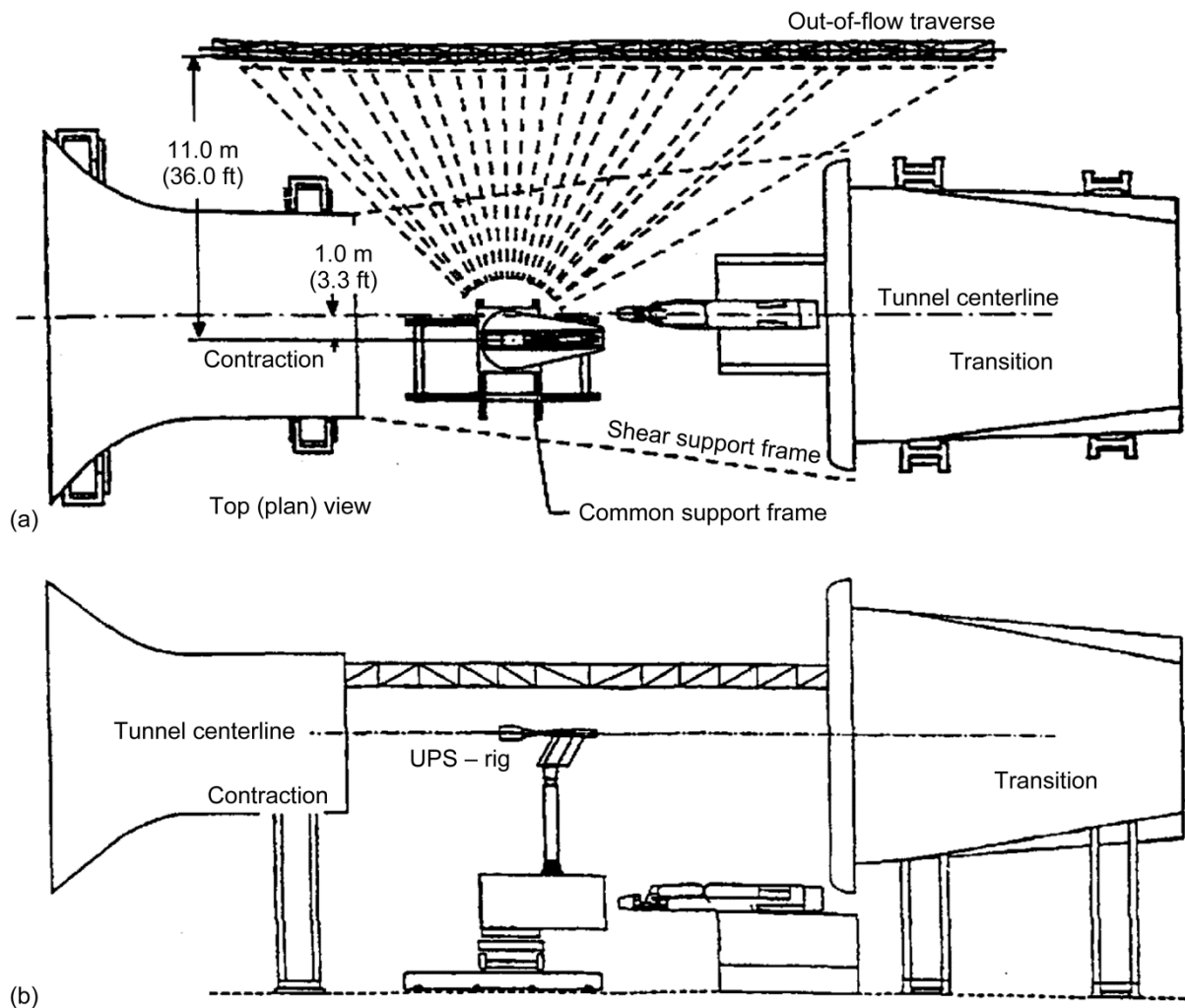


Figure 6.—Sketch of the UPS model installed in the DNW facility showing layout of microphones located outside of the free jet. (a) Top (plan) view. (b) Side view.

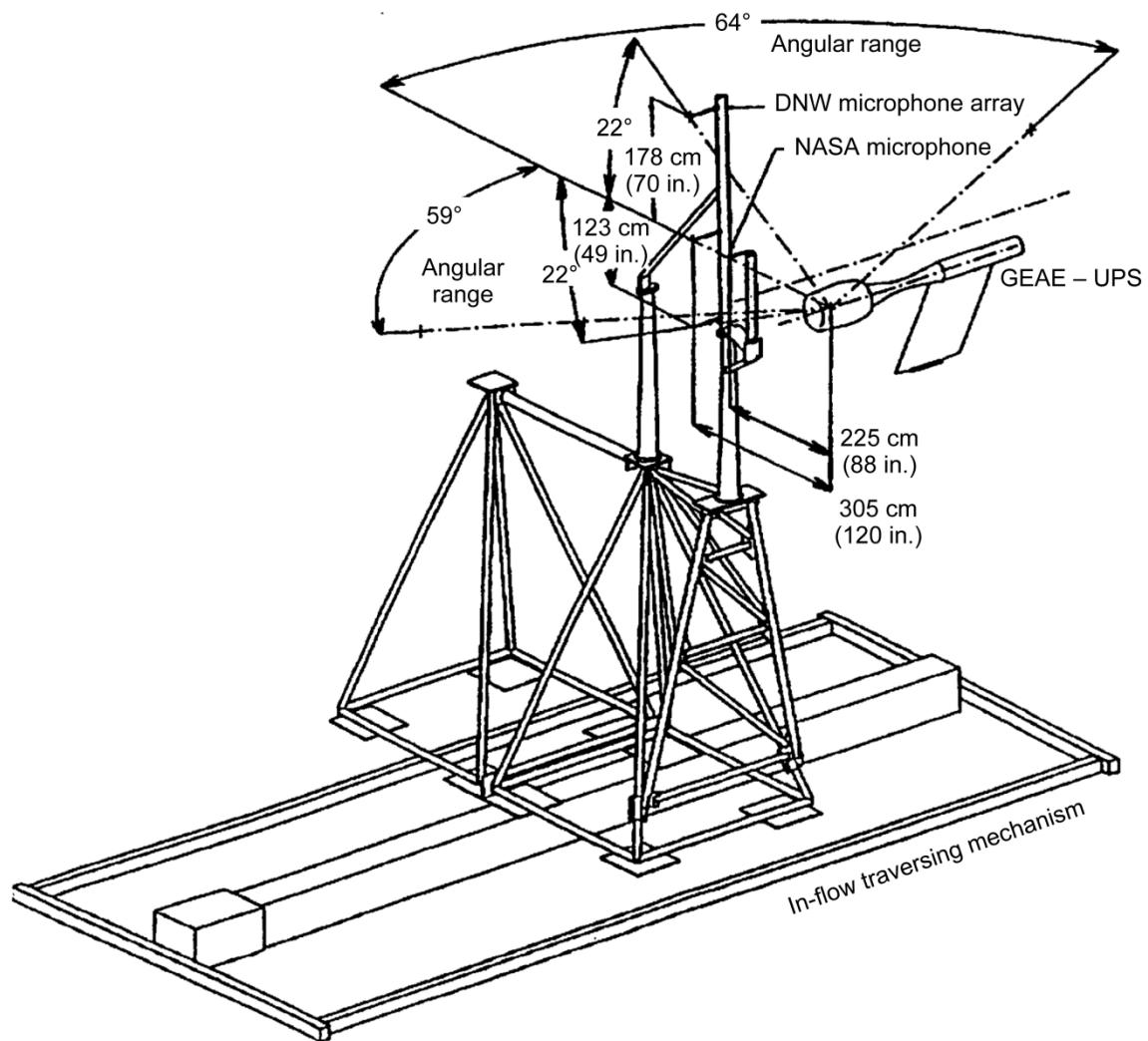


Figure 7.—Sketch of the UPS model installed in the DNW facility showing microphones located within the free jet.

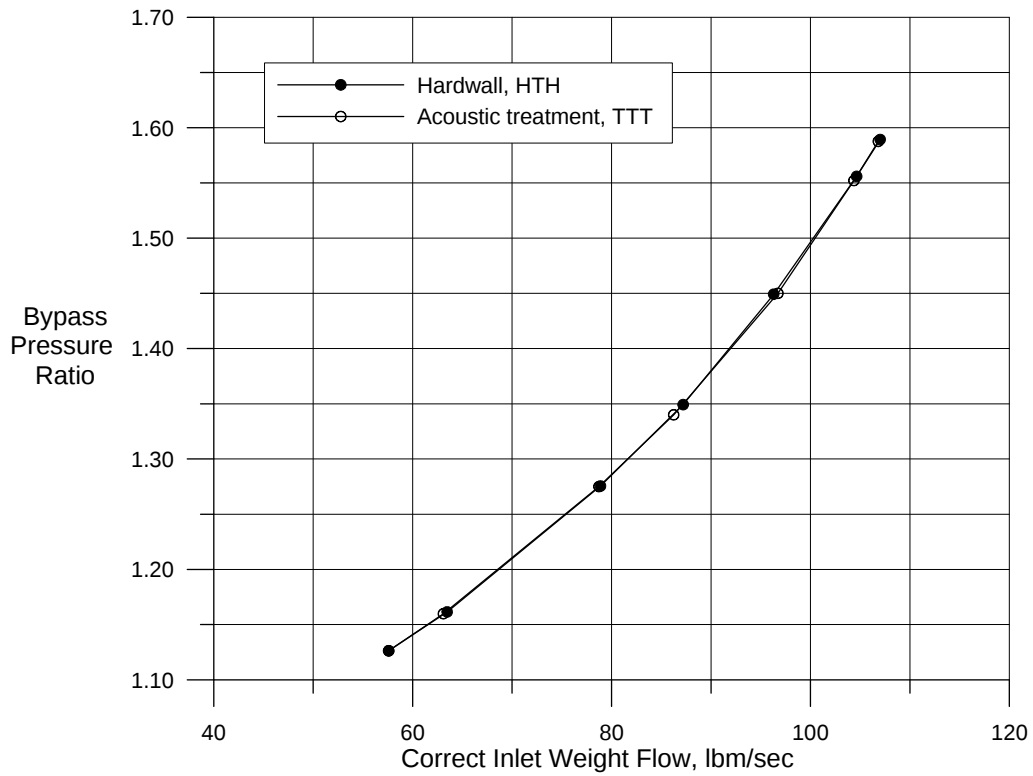


Figure 8.—Fan stage aerodynamic performance in the 9×15 LSWT for the M4 rotor.

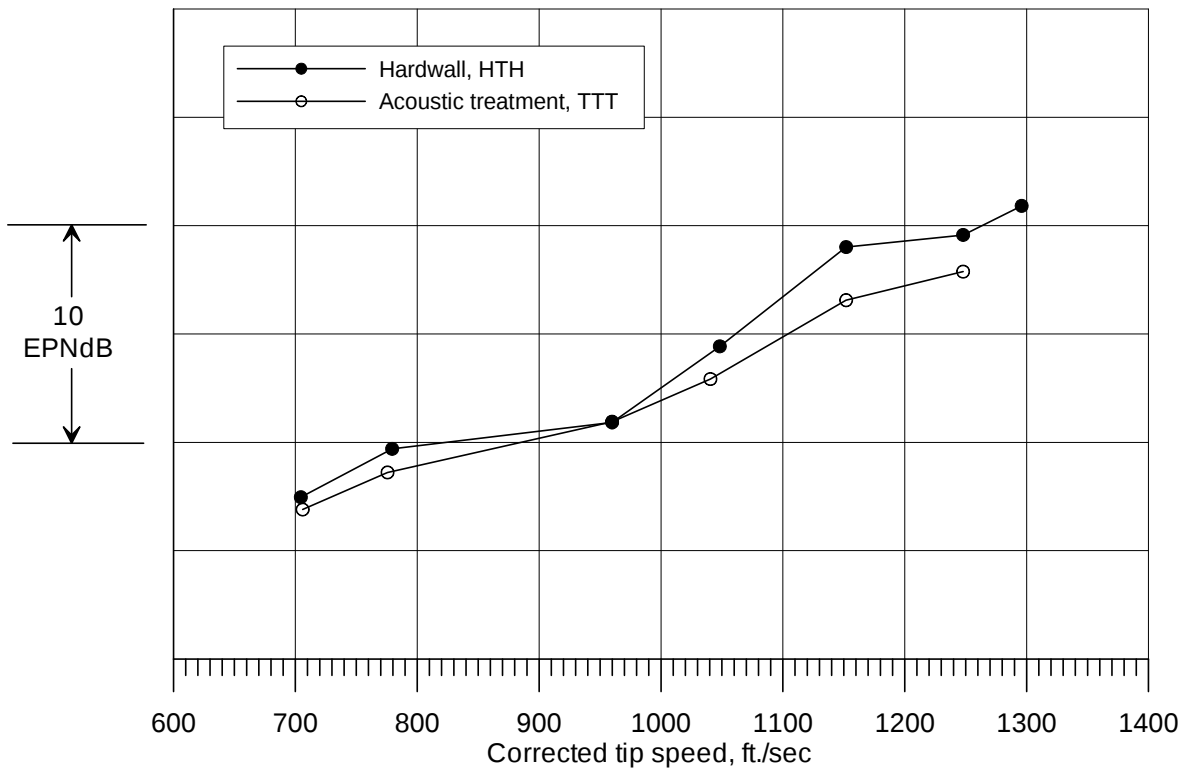


Figure 9.—Effect of rotor bypass duct acoustic treatment for the baseline M4 metal rotor. (EPNL calculated from 9×15 LSWT sideline data, 0° AOA, 5.6 scale factor, 304.8-m (1000-ft) flyover).

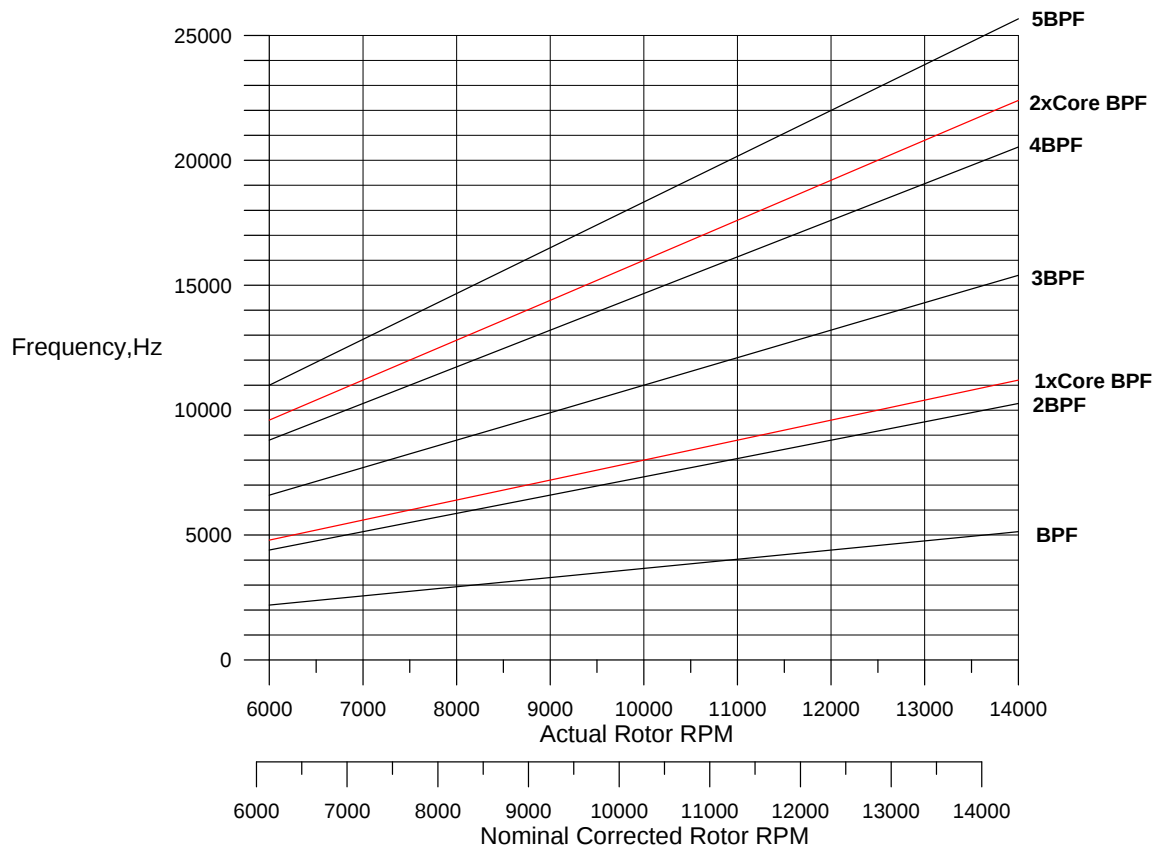


Figure 10.—UPS bypass and core tone frequencies as a function of rotor speed.

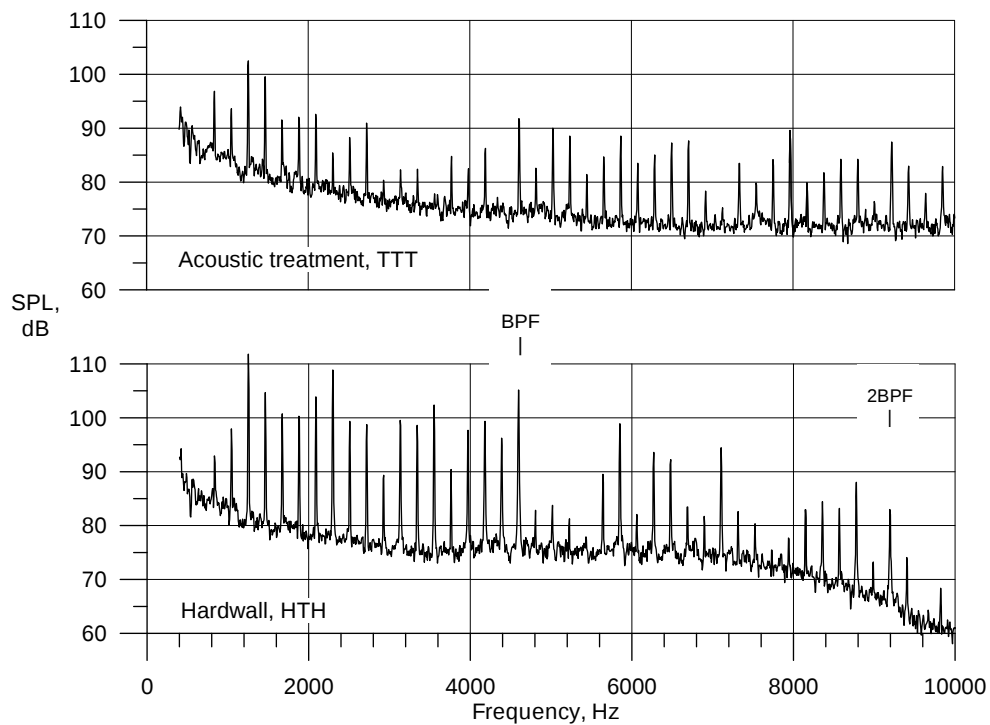


Figure 11.—Constant bandwidth (6 Hz) spectra. (M4 metal rotor, 74° sideline emission angle, 89 in. sideline, 12 k rpm_c, NASA 9×15 LSWT).

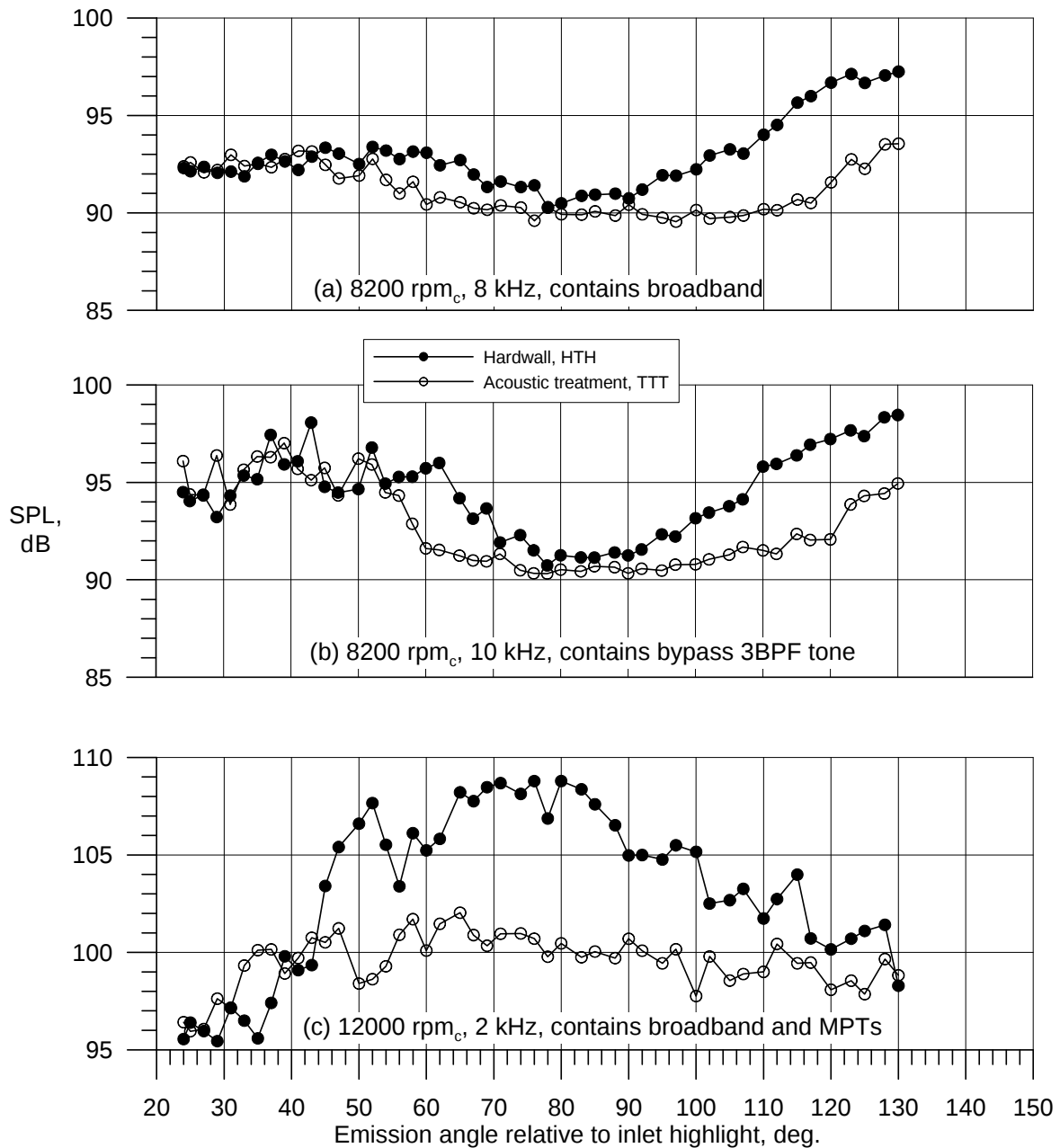


Figure 12.— $1/3^{\text{rd}}$ octave directivities for hard-wall and acoustic treatment configurations (Baseline M4 metal rotor, 9×15 LSWT).

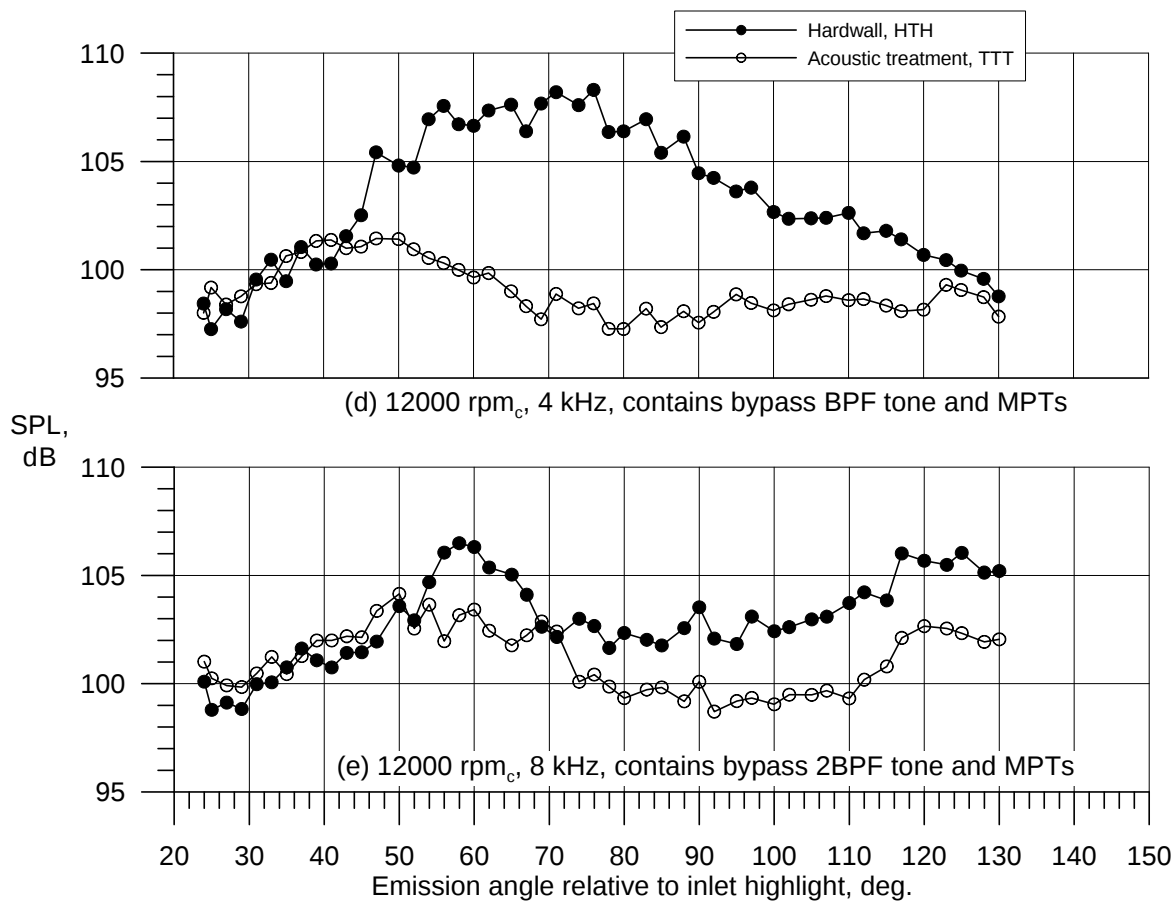


Figure 12.—Concluded.

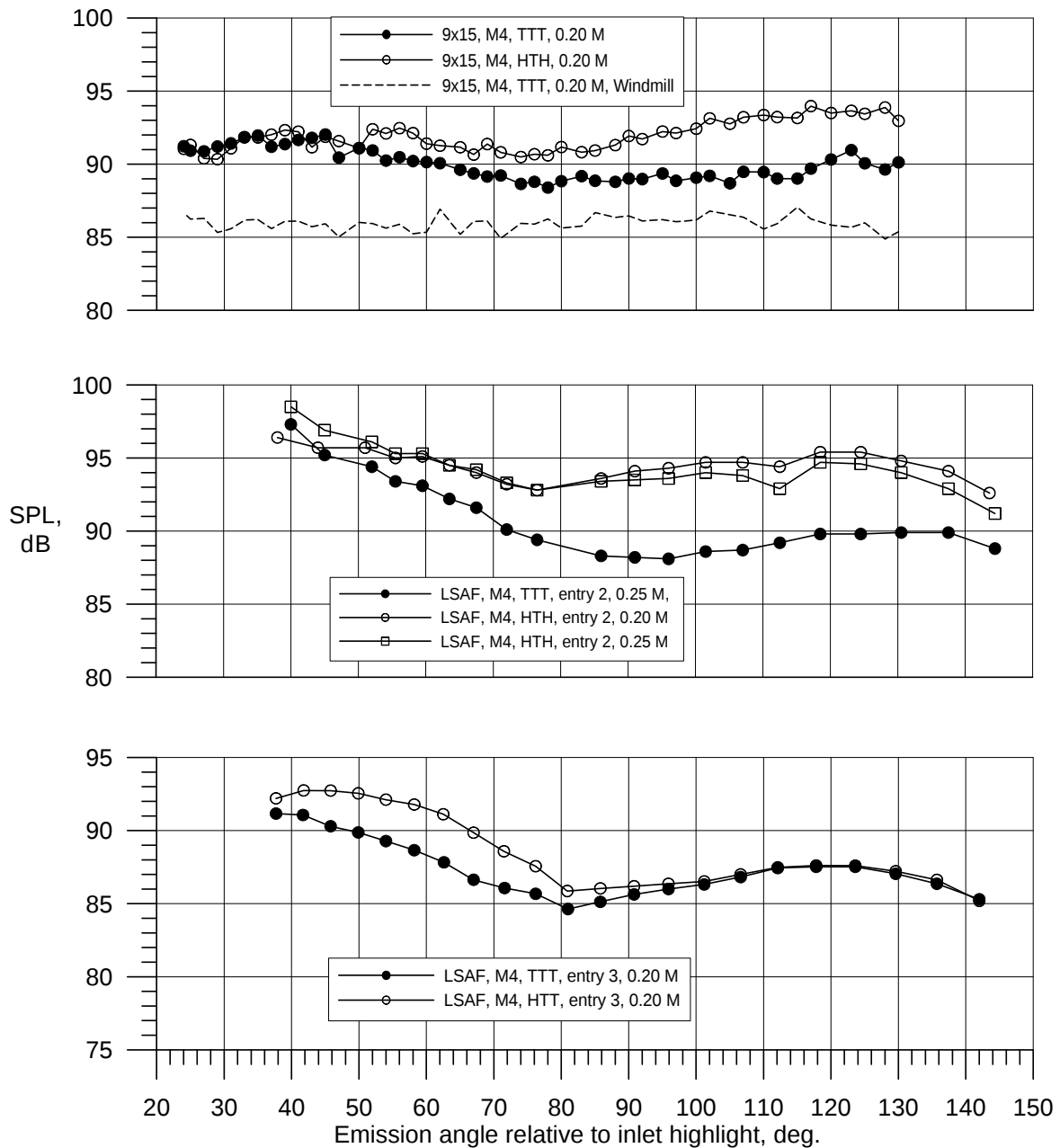


Figure 13.—Effect of inlet and exhaust acoustic liner for NASA 9x15 LSWT and Boeing LSAF entries (8.2 k rpm_c, 1/3rd octave directivities at 5 kHz (broadband spectral region), LSAF data adjusted to 88-in. sideline).

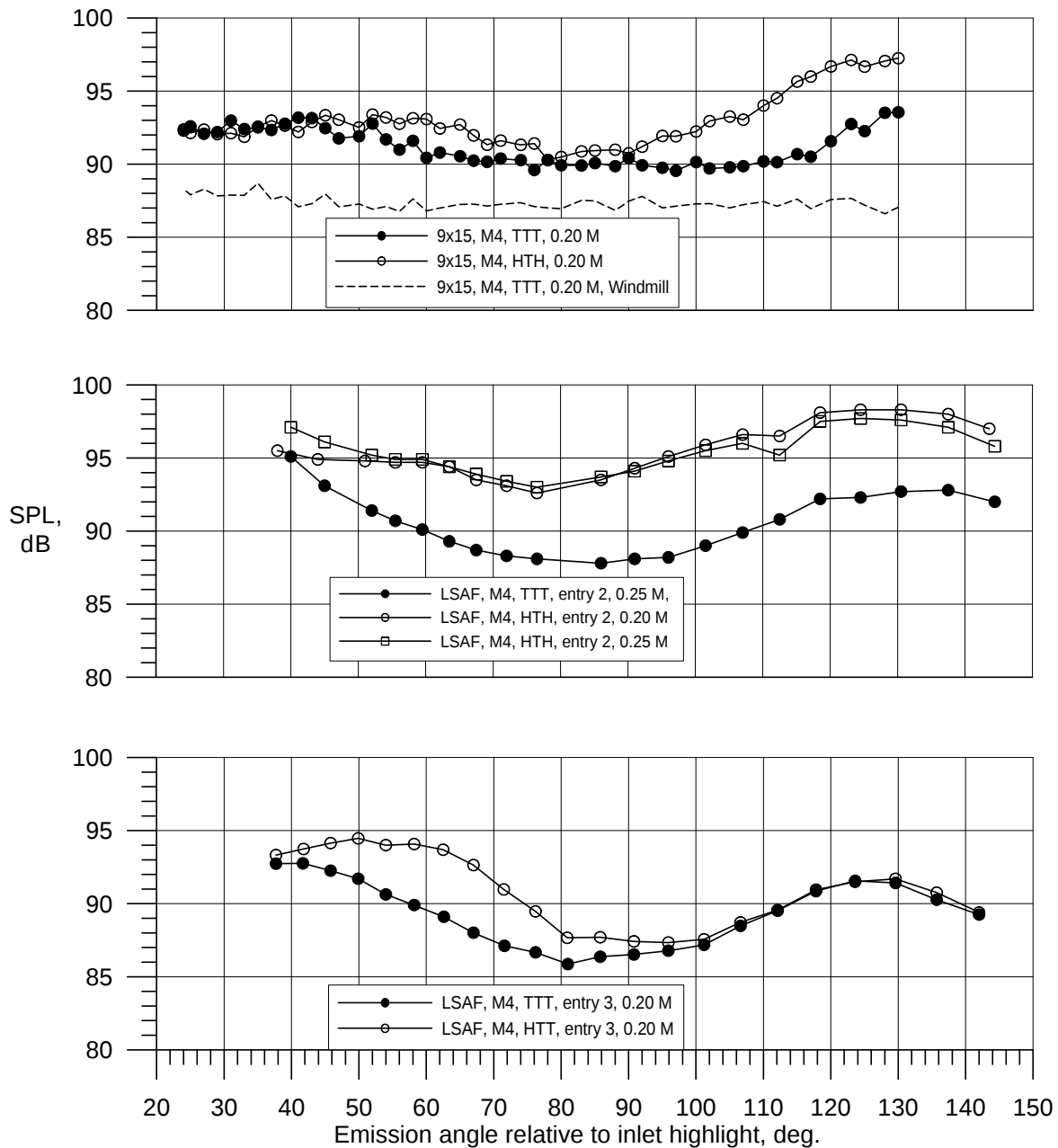


Figure 14.—Effect of inlet and exhaust acoustic liner for NASA 9×15 LSWT and Boeing LSAF entries (8.2 k rpm_c, 1/3rd octave directivities at 8 kHz (broadband spectral region), LSAF data adjusted to 88-in. sideline).

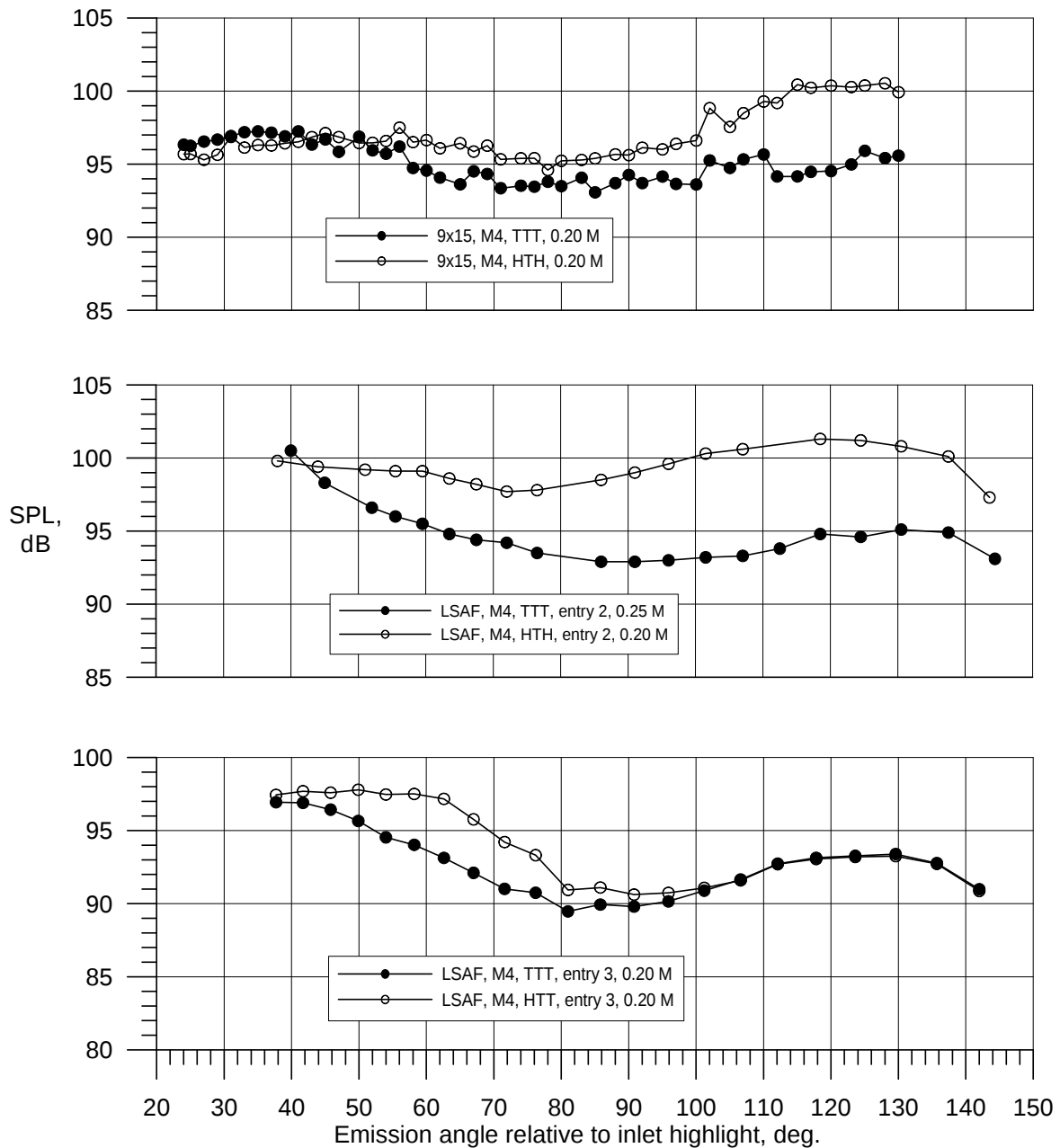


Figure 15.—Effect of inlet and exhaust acoustic liner for NASA 9×15 LSWT and Boeing LSAF entries (10 k rpm_c, 1/3rd octave directivities at 6.3 kHz (broadband spectral region), LSAF data adjusted to 88-in. sideline).

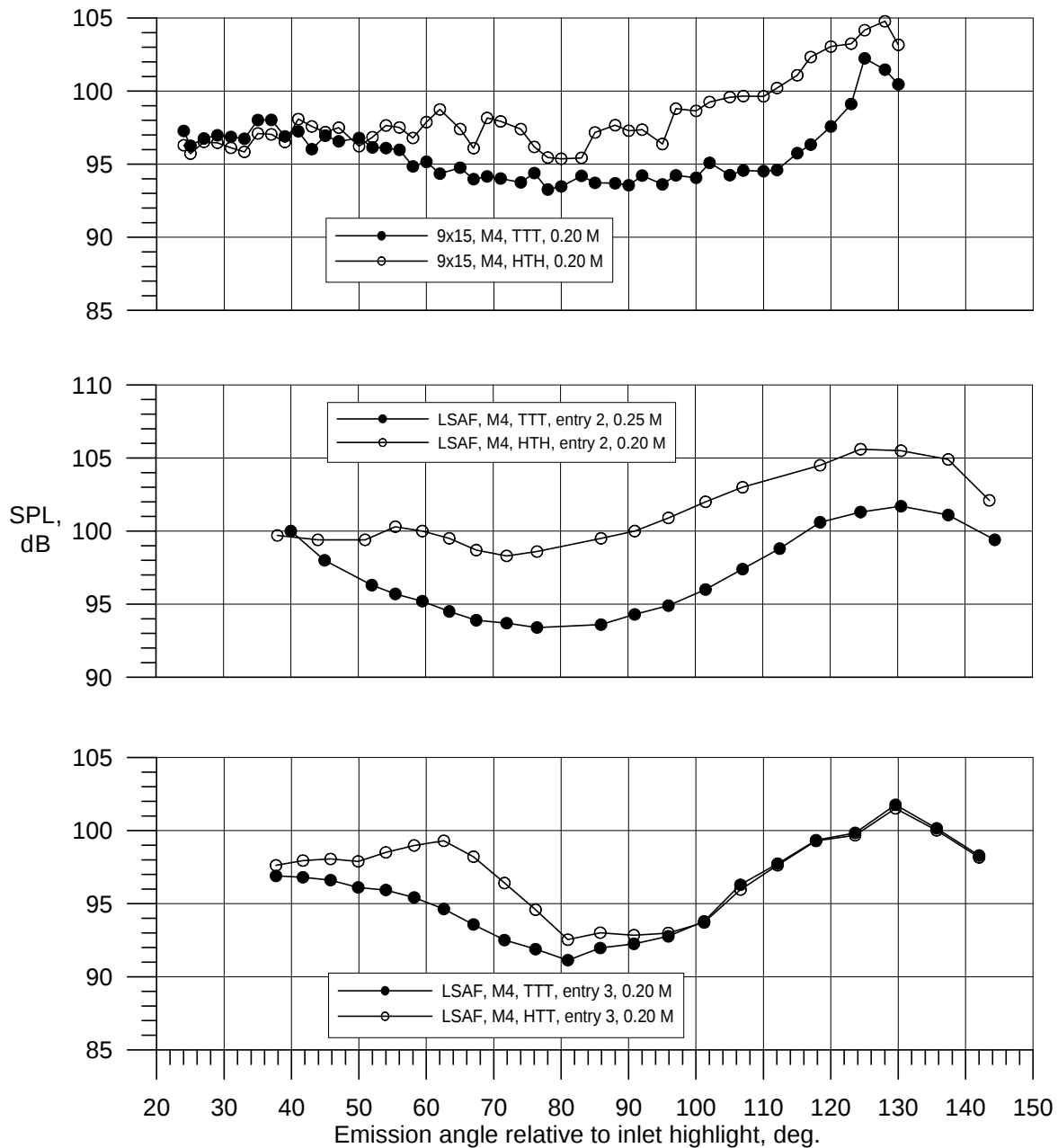


Figure 16.—Effect of inlet and exhaust acoustic liner for NASA 9×15 LSWT and Boeing LSAF entries (10 k rpm_c, 1/3rd octave directivities at 8 kHz (1/3rd octave band contains bypass 2BPF and core BPF tones), LSAF data adjusted to 88-in. sideline).

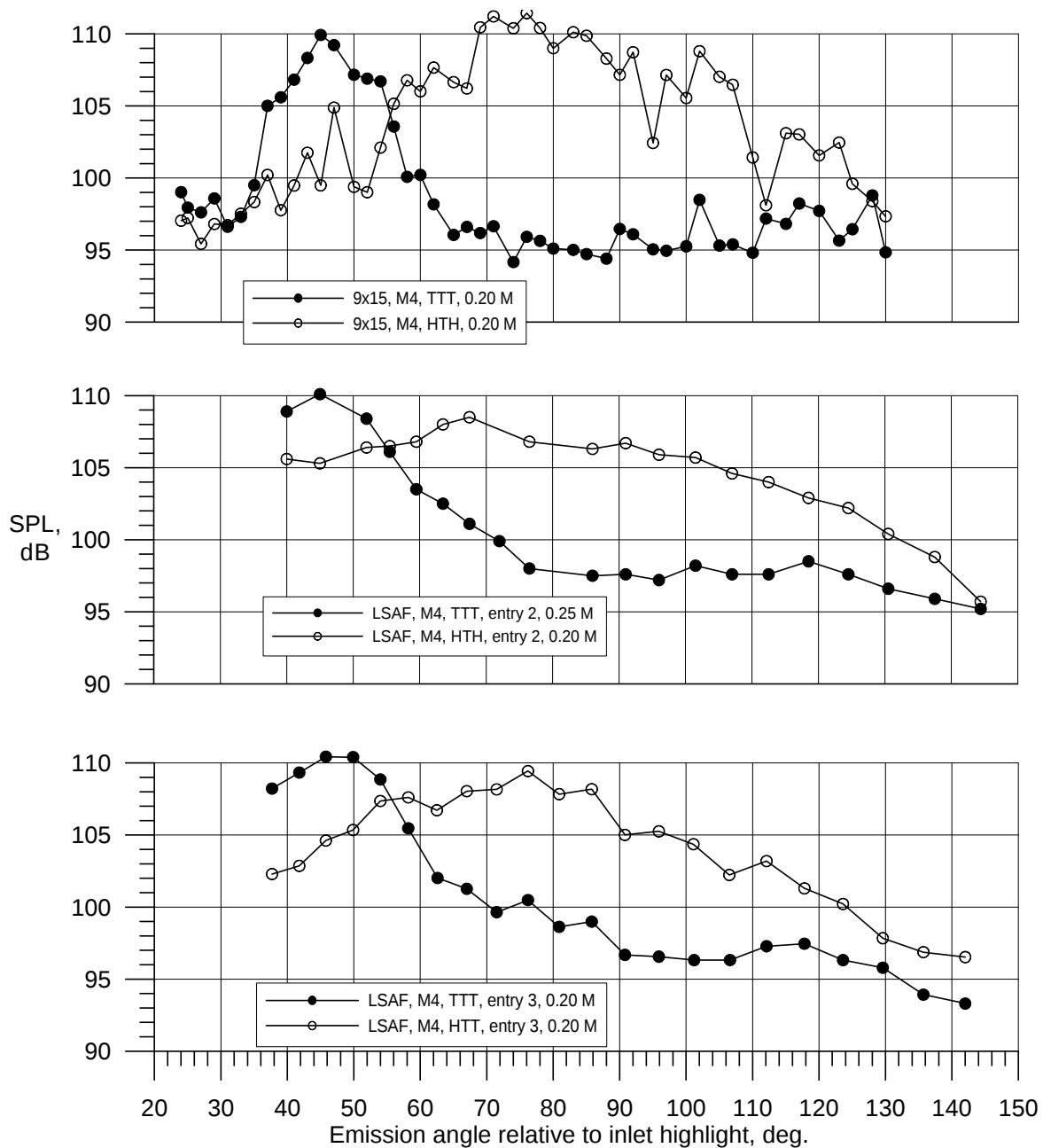


Figure 17.—Effect of inlet and exhaust acoustic liner for NASA 9×15 LSWT and Boeing LSAF entries (11 k rpm_c, 1/3rd octave directivities at 4 kHz (1/3rd octave band contains MPT and bypass BPF tones), LSAF data adjusted to 88-in. sideline).

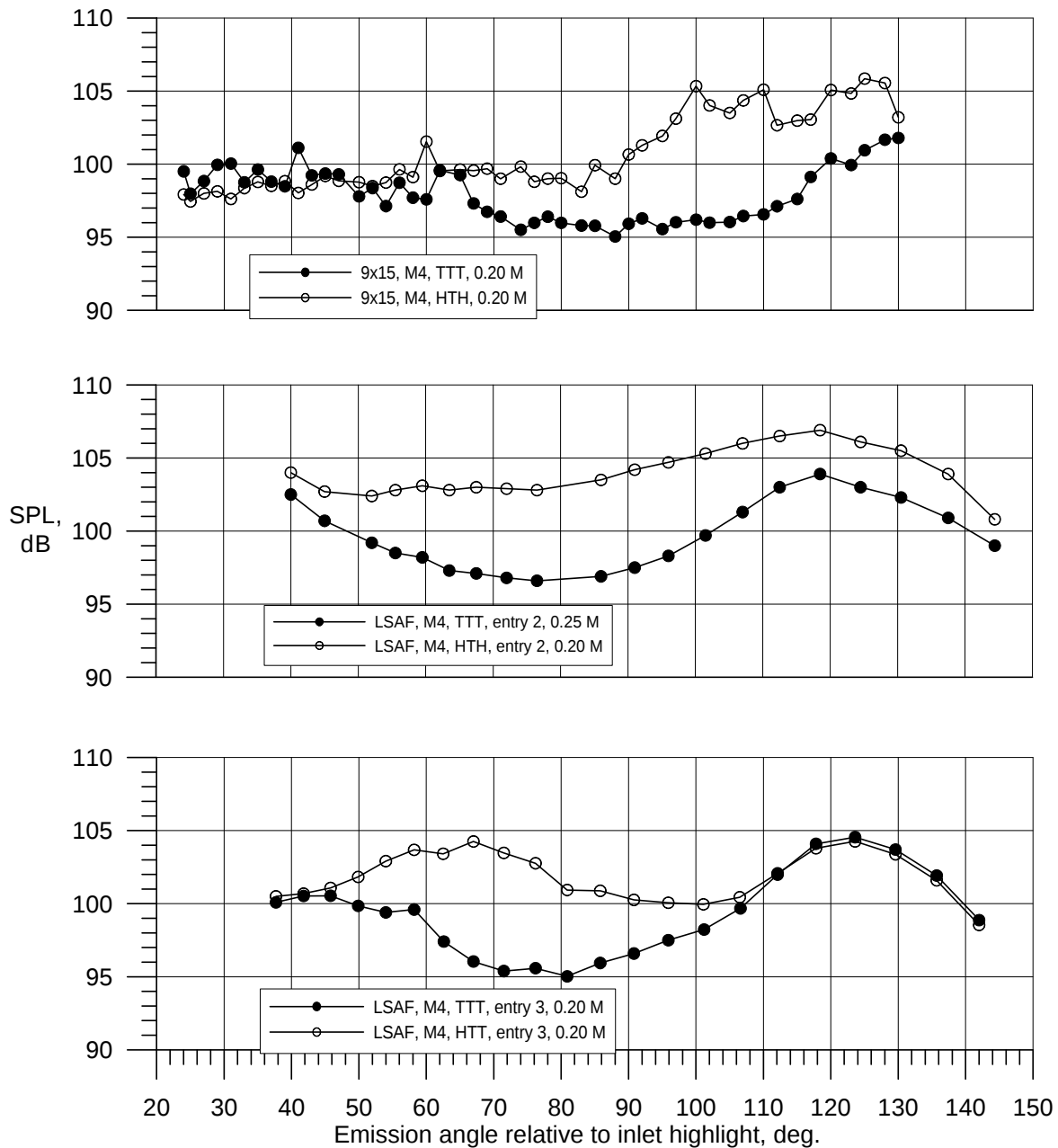


Figure 18.—Effect of inlet and exhaust acoustic liner for NASA 9x15 LSWT and Boeing LSAF entries (11 k rpm_c, 1/3rd octave directivities at 8 kHz (1/3rd octave band contains MPT, bypass 2BPF and core BPF tones), LSAF data adjusted to 88-in. sideline).

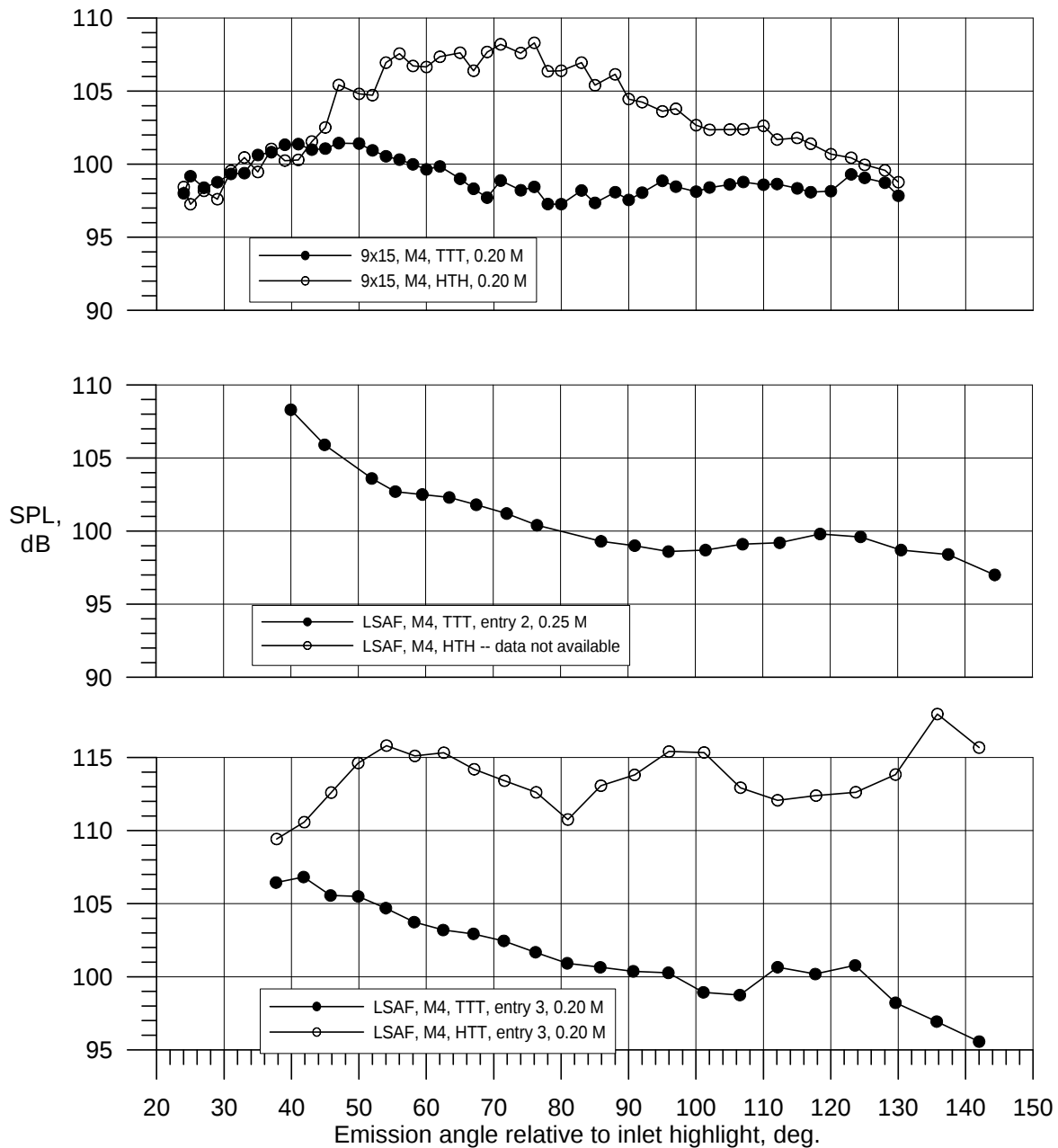


Figure 19.—Effect of inlet and exhaust acoustic liner for NASA 9×15 LSWT and Boeing LSAF entries (12 k rpm_c, 1/3rd octave directivities at 4 kHz (1/3rd octave band contains MPT and bypass BPF tones), LSAF data adjusted to 88-in. sideline).

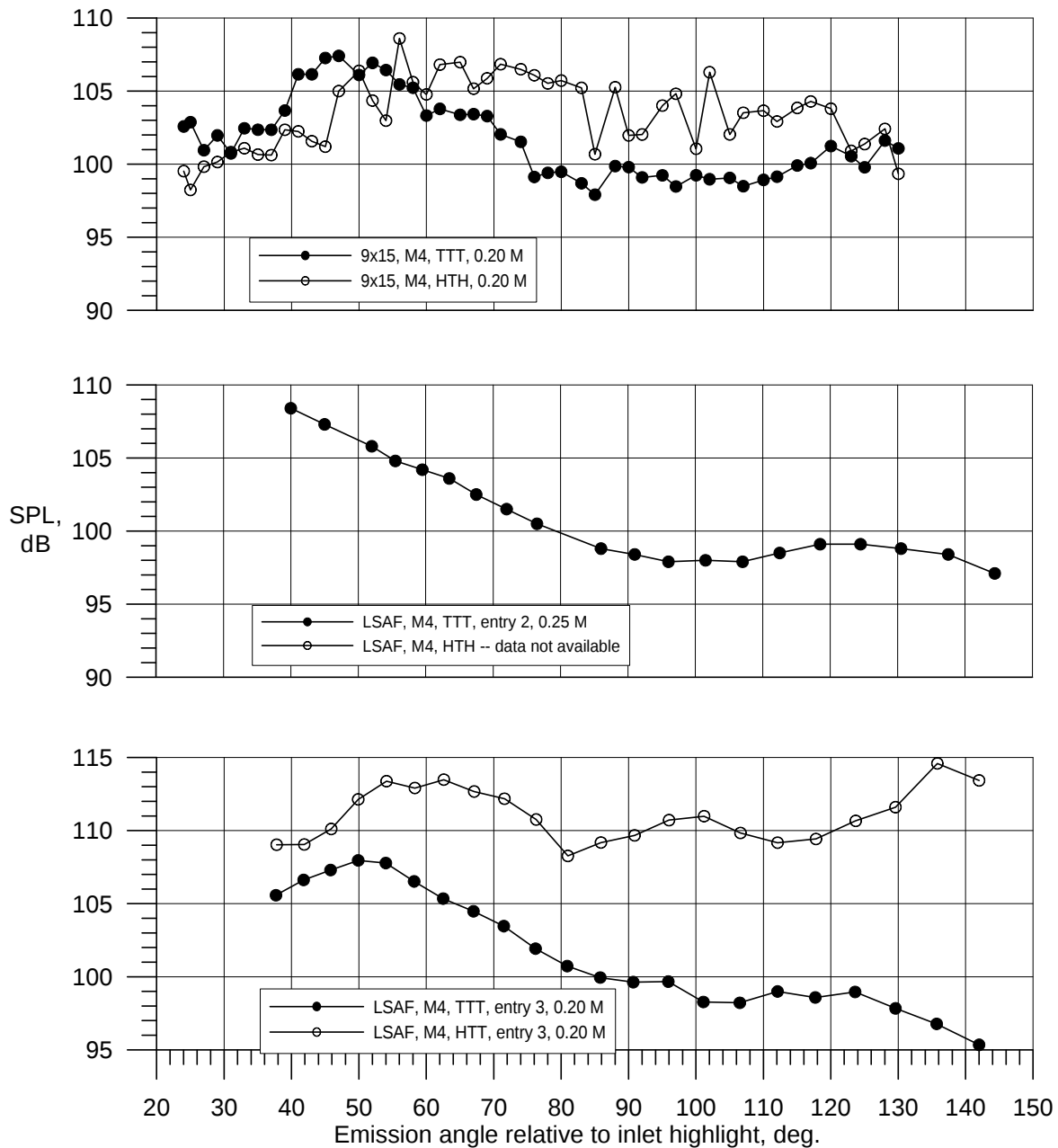


Figure 20.—Effect of inlet and exhaust acoustic liner for NASA 9x15 LSWT and Boeing LSAF entries (12 k rpm_c, 1.3rd octave directivities at 5 kHz (1/3rd octave band contains MPT and bypass BPF tones), LSAF data adjusted to 88-in. sideline).

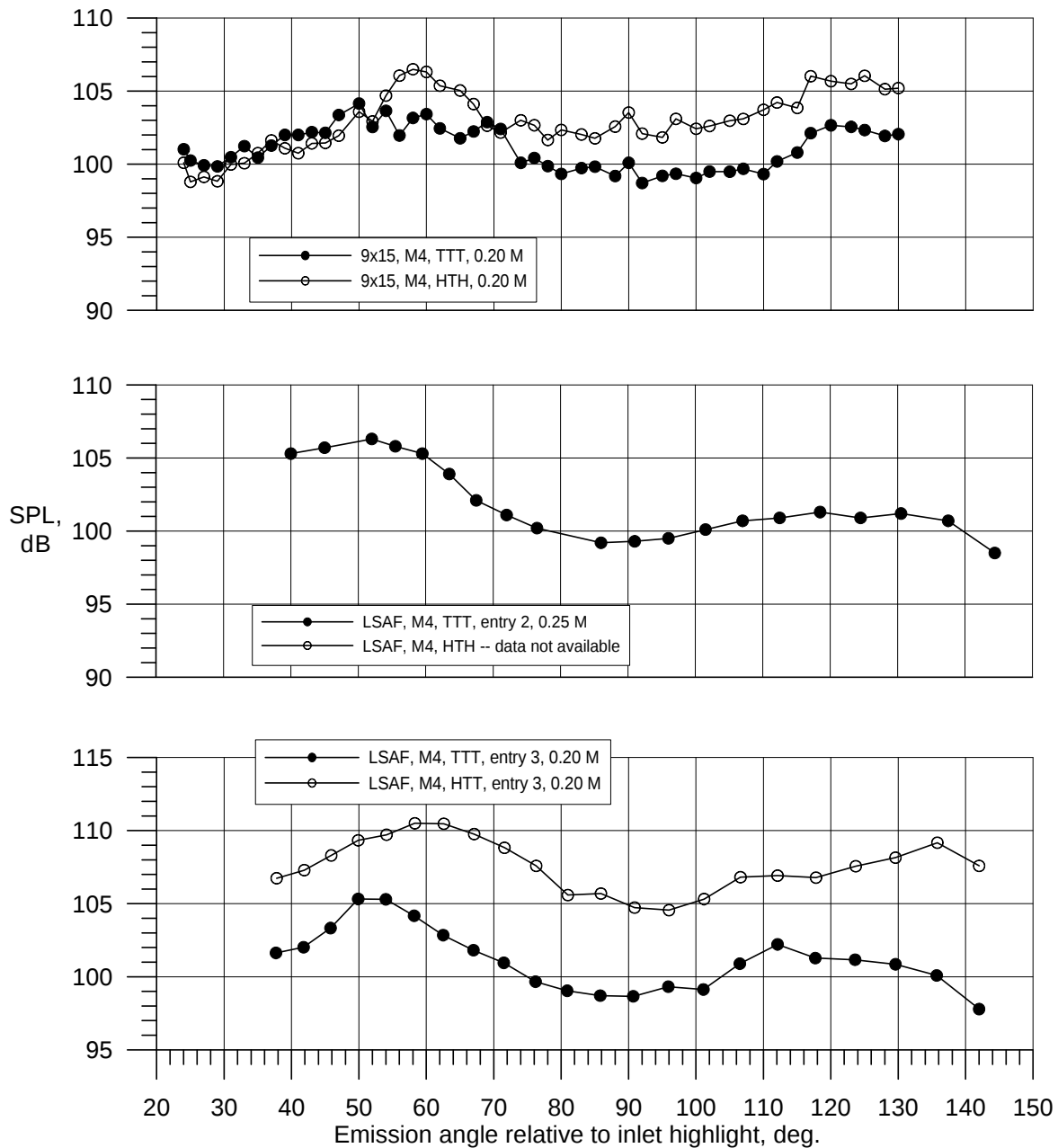


Figure 21.—Effect of inlet and exhaust acoustic liner for NASA 9x15 LSWT and Boeing LSAF entries (12 k rpm_c, 1/3rd octave directivities at 8 kHz (1/3rd octave band contains MPT and bypass 2BPF tones), LSAF data adjusted to 88-in. sideline).

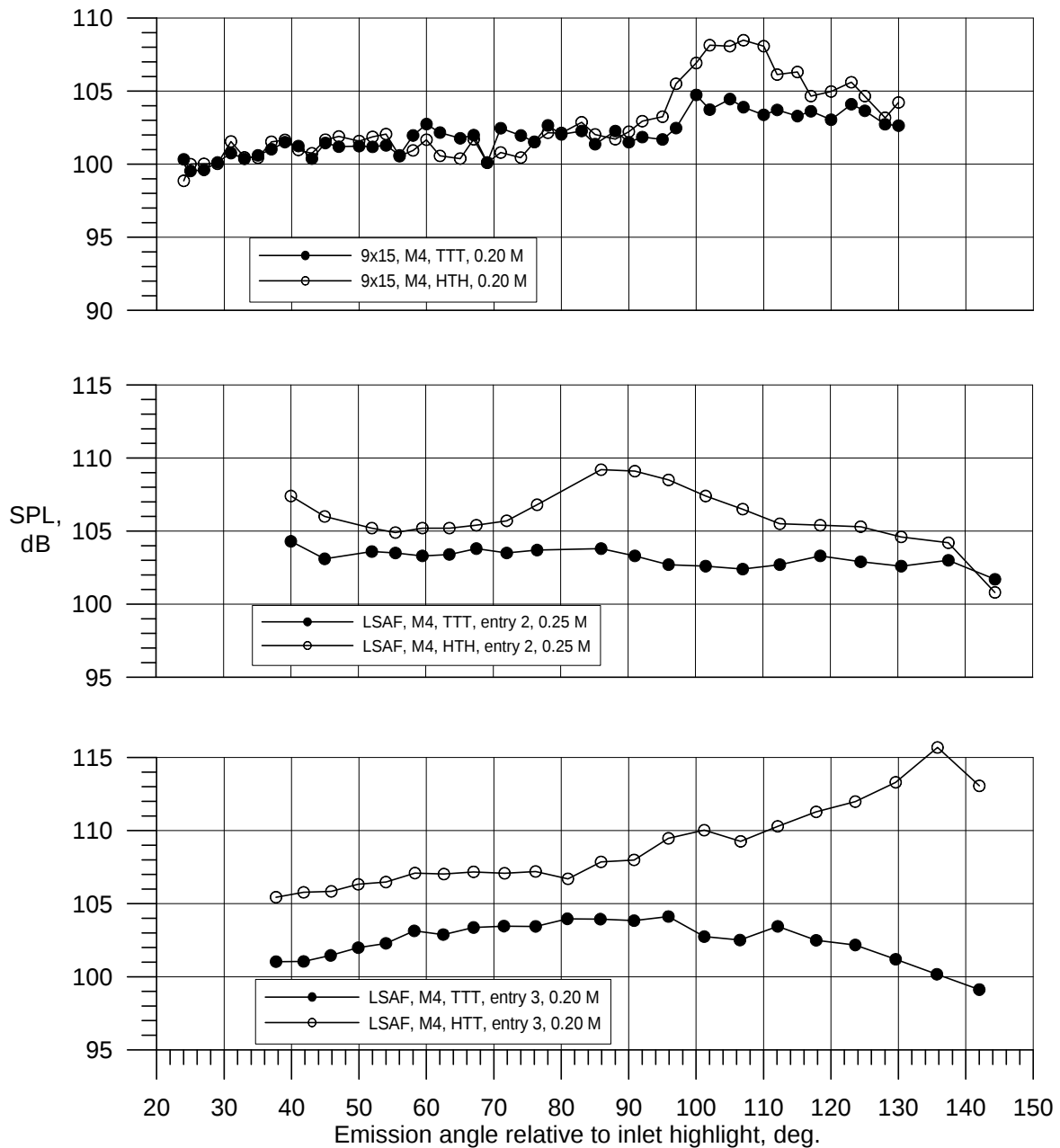


Figure 22.—Effect of inlet and exhaust acoustic liner for NASA 9x15 LSWT and Boeing LSAF entries (13 k rpm_c, 1/3rd octave directivities at 4 kHz (MPT and broadband spectral region), LSAF data adjusted to 88-in. sideline).

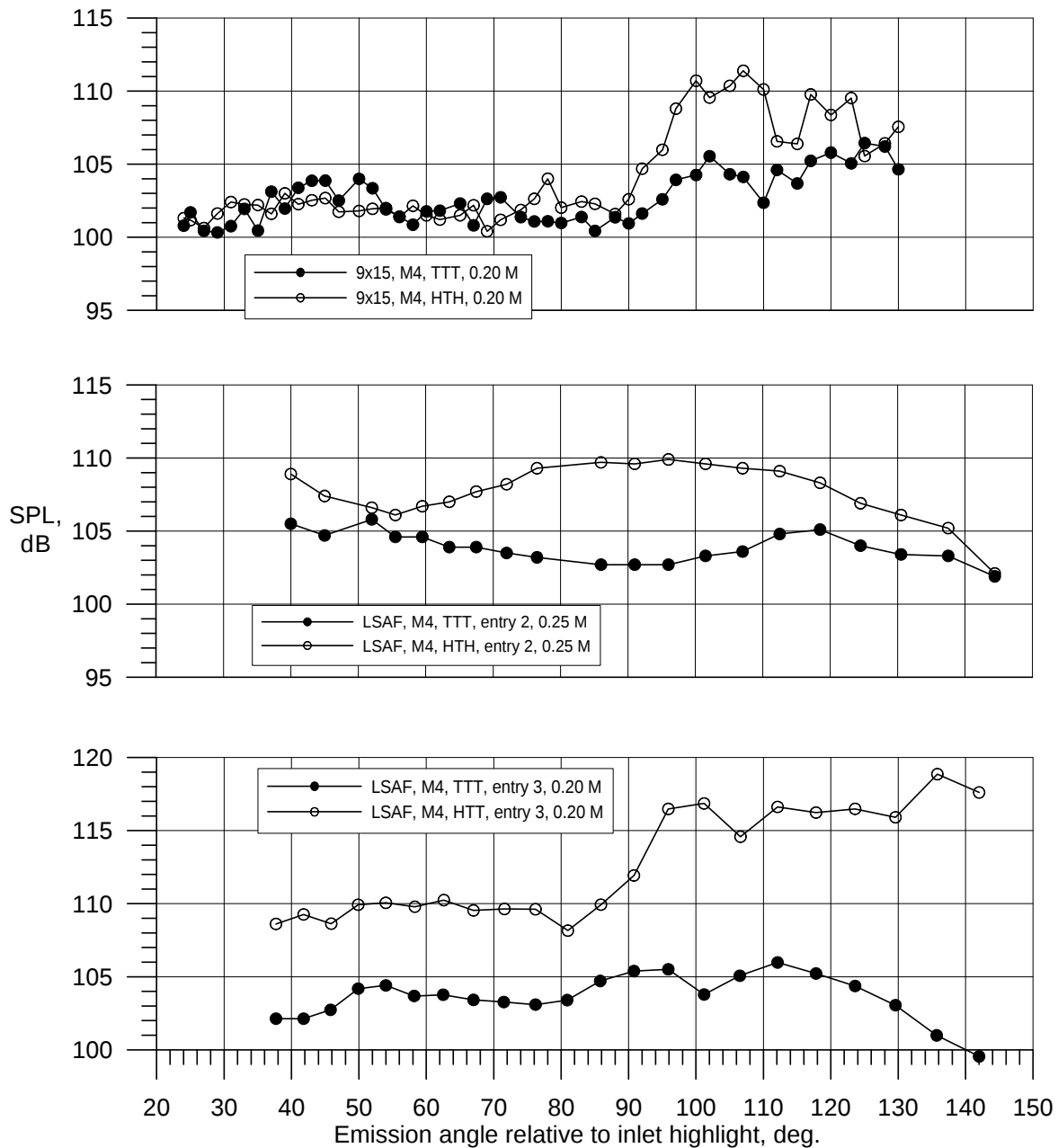


Figure 23.—Effect of inlet and exhaust acoustic liner for NASA 9×15 LSWT and Boeing LSAF entries (13 k rpm_c, 1/3rd octave directivities at 5 kHz (1/3rd octave band contains MPT and bypass BPF tones), LSAF data adjusted to 88-in. sideline).

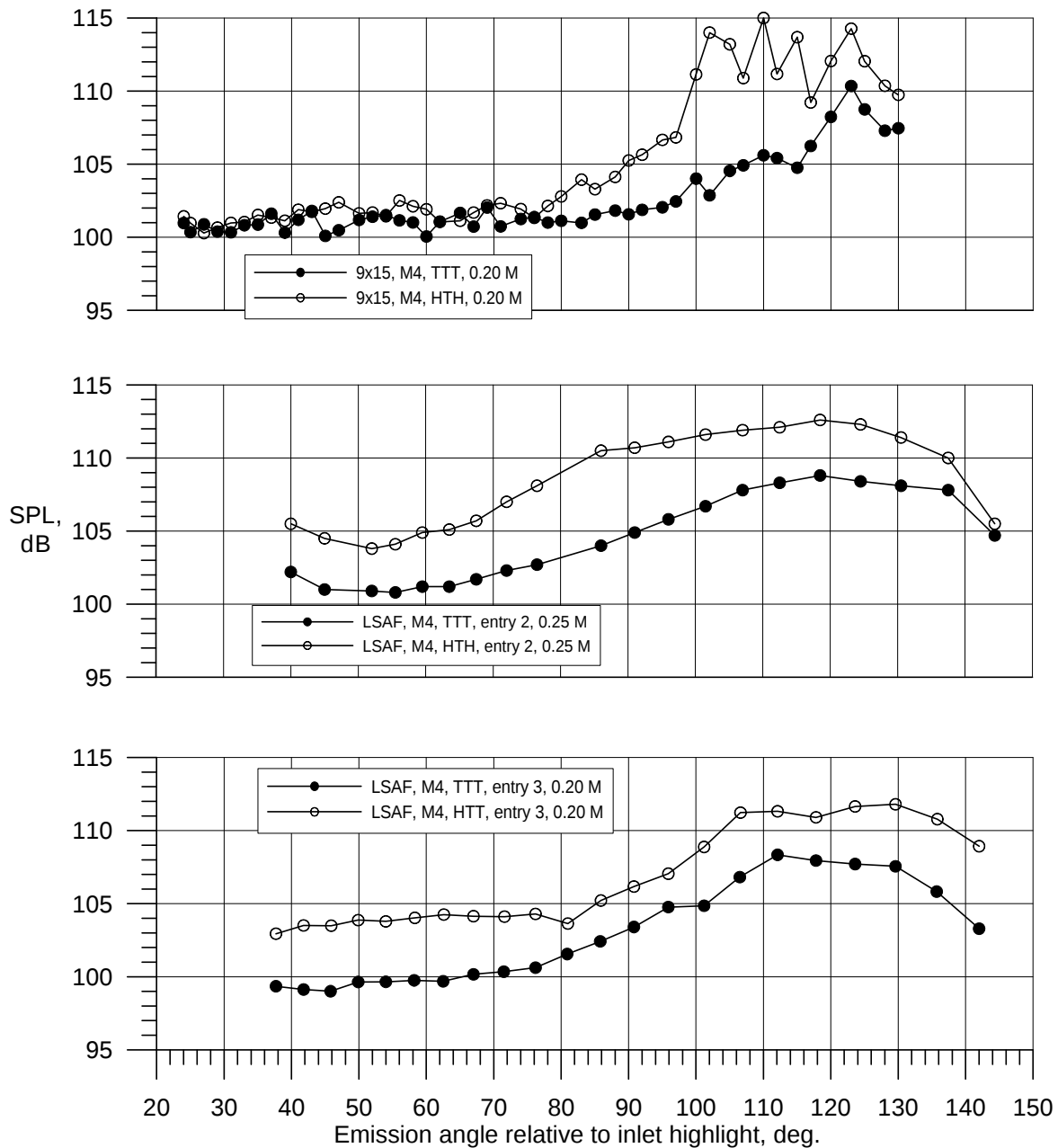


Figure 24.—Effect of inlet and exhaust acoustic liner for NASA 9x15 LSWT and Boeing LSAF entries (13 k rpm_c, 1/3rd octave directivities at 10 kHz (1/3rd octave band contains MPT, bypass 2BPF and core BPF tones), LSAF data adjusted to 88-in. sideline).

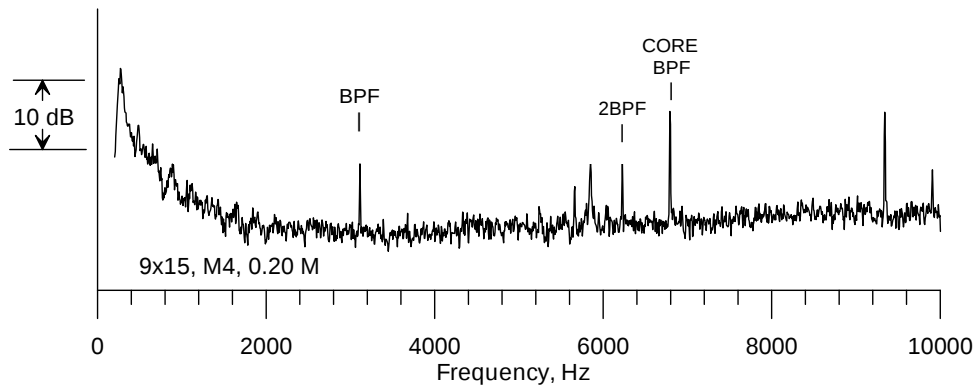
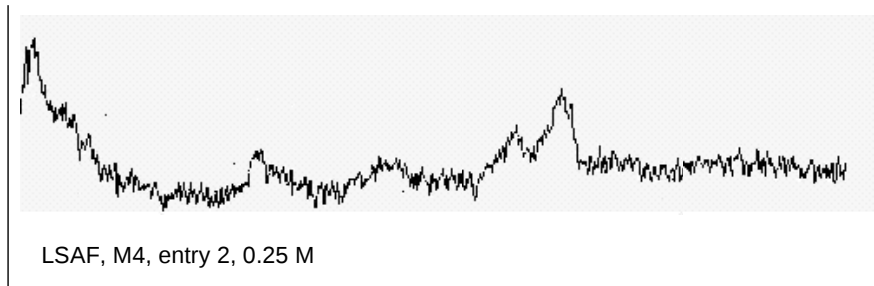


Figure 25.—Comparison of 6 Hz bandwidth spectra taken in the NASA 9×15 LSWT and the Boeing LSAF showing shear layer distortion of the tonal content (8.2 k rpm_c, 130° sideline emission angle, HTH).

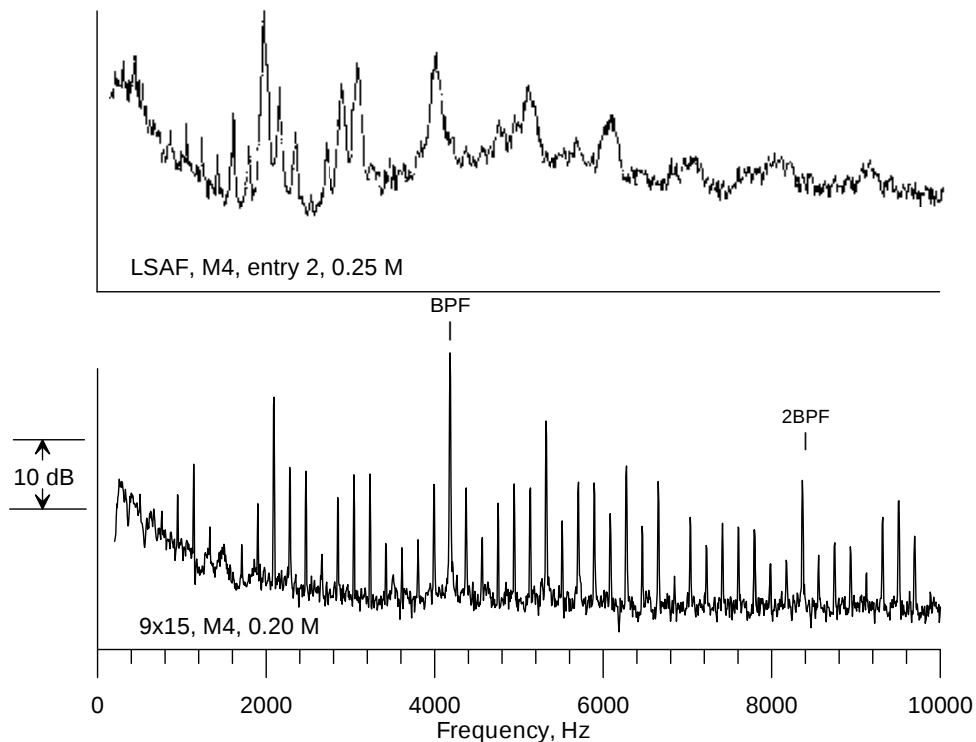


Figure 26.—Comparison of 6 Hz bandwidth spectra taken in the NASA 9×15 LSWT and the Boeing LSAF showing shear layer distortion of the tonal content (11 k rpm_c, 75° sideline emission angle, HTH).

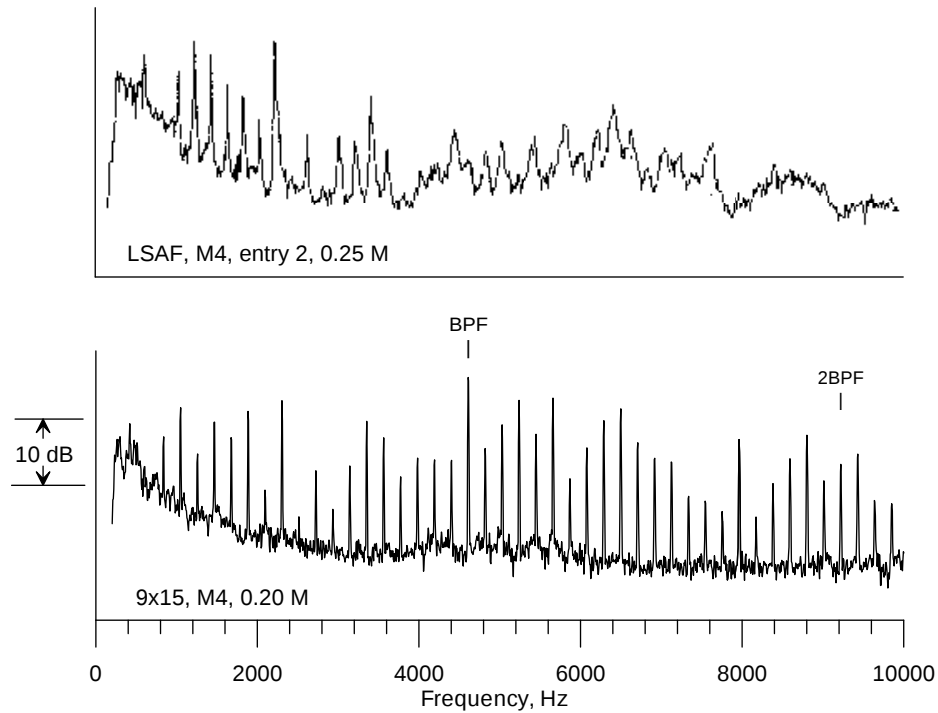


Figure 27.—Comparison of 6 Hz bandwidth spectra taken in the NASA 9×15 LSWT and the Boeing LSAF showing shear layer distortion of the tonal content (12 k rpm_c, 50° sideline emission angle, TTT).

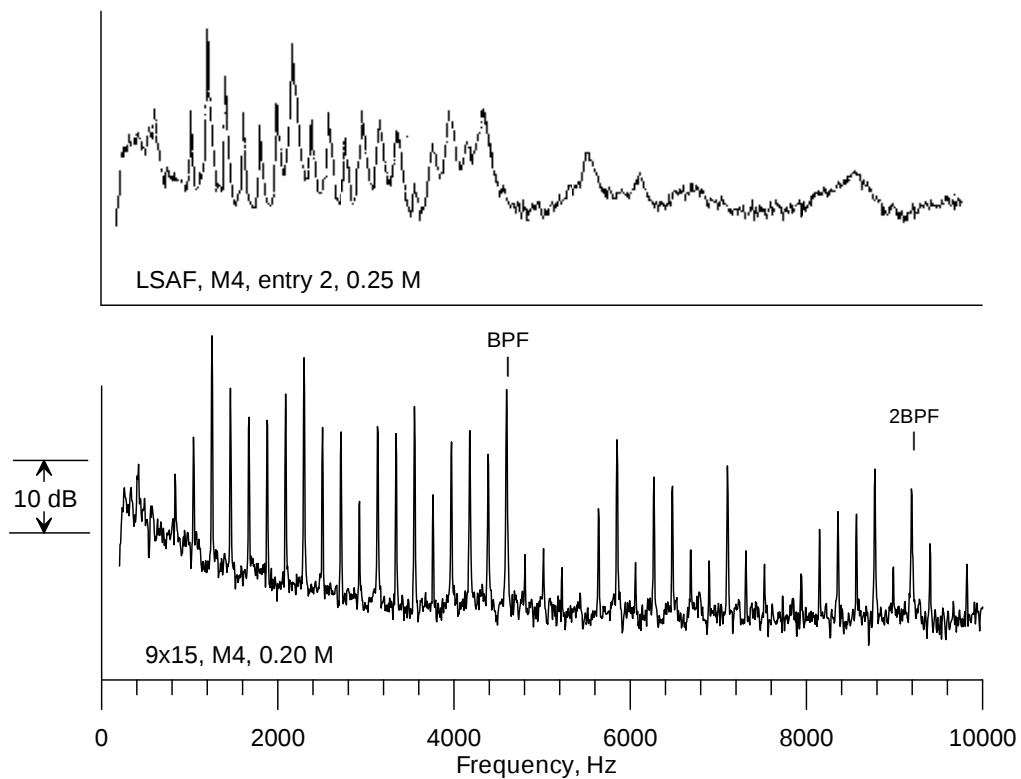


Figure 28.—Comparison of 6 Hz bandwidth spectra taken in the NASA 9×15 LSWT and the Boeing LSAF showing shear layer distortion of the tonal content (12 k rpm_c, 75° sideline emission angle, HTH).

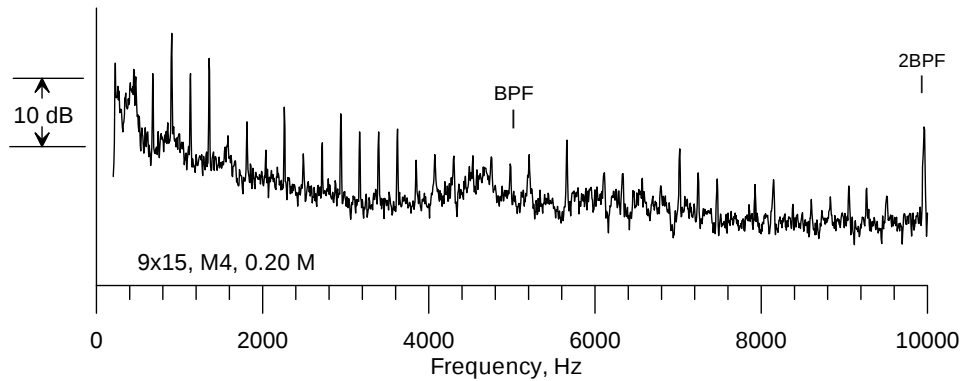
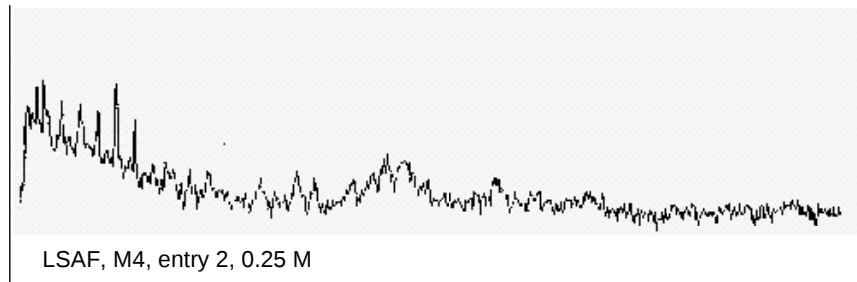


Figure 29.—Comparison of 6 Hz bandwidth spectra taken in the NASA 9×15 LSWT and the Boeing LSAF showing shear layer distortion of the tonal content (13 k rpm_c, 50° sideline emission angle, HTH).

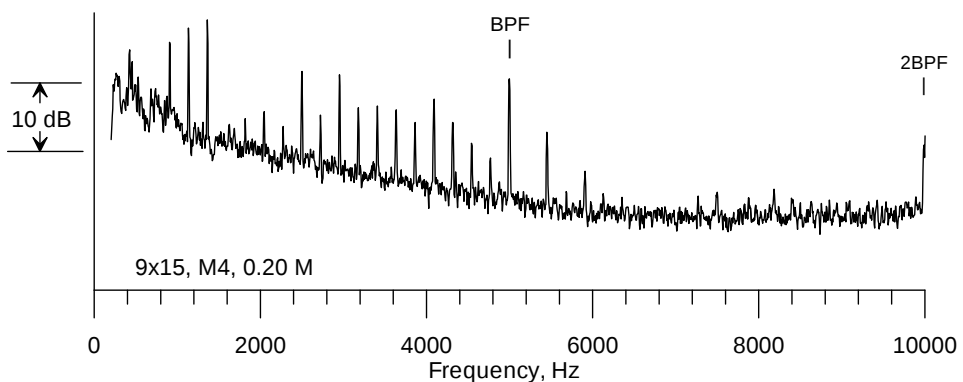
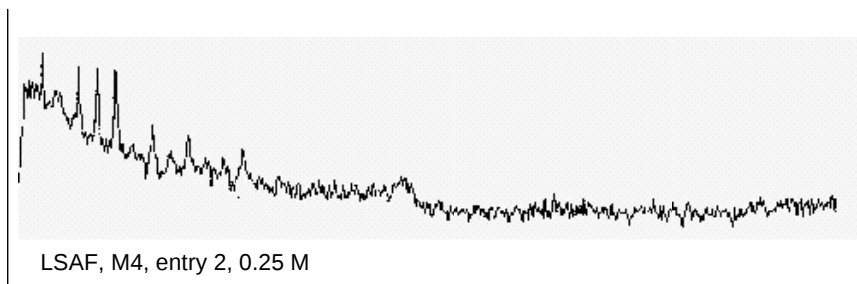


Figure 30.—Comparison of 6 Hz bandwidth spectra taken in the NASA 9×15 LSWT and the Boeing LSAF showing shear layer distortion of the tonal content (13 k rpm_c, 100° sideline emission angle, TTT).

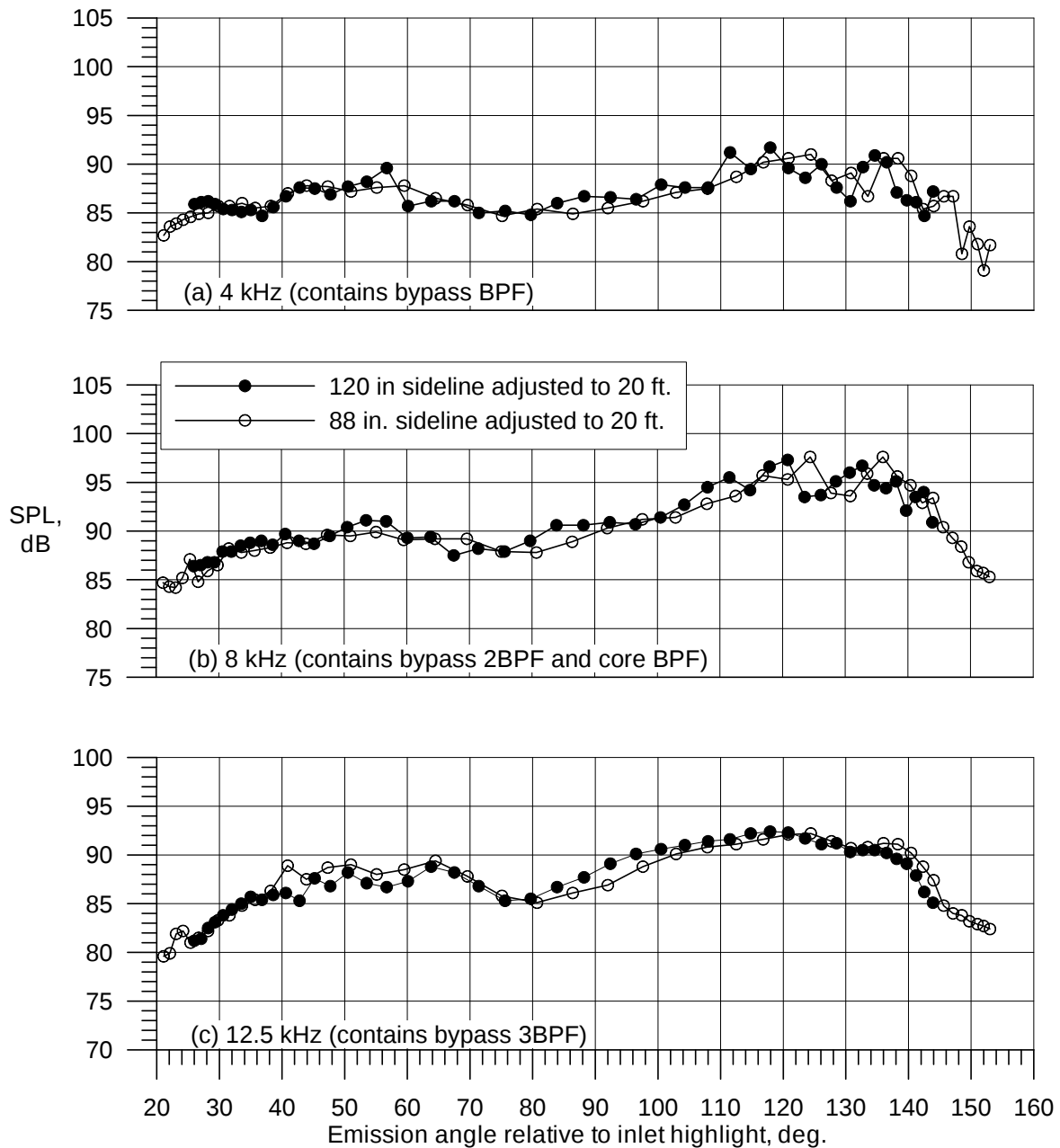


Figure 31.—Comparison of $1/3^{\text{rd}}$ octave directivities obtained within a Mach number 0.20 free jet in the DNW facility at 88- and 120-in. sidelines (10 k rpm_c, data adjusted to a 20-ft sideline, HTH).

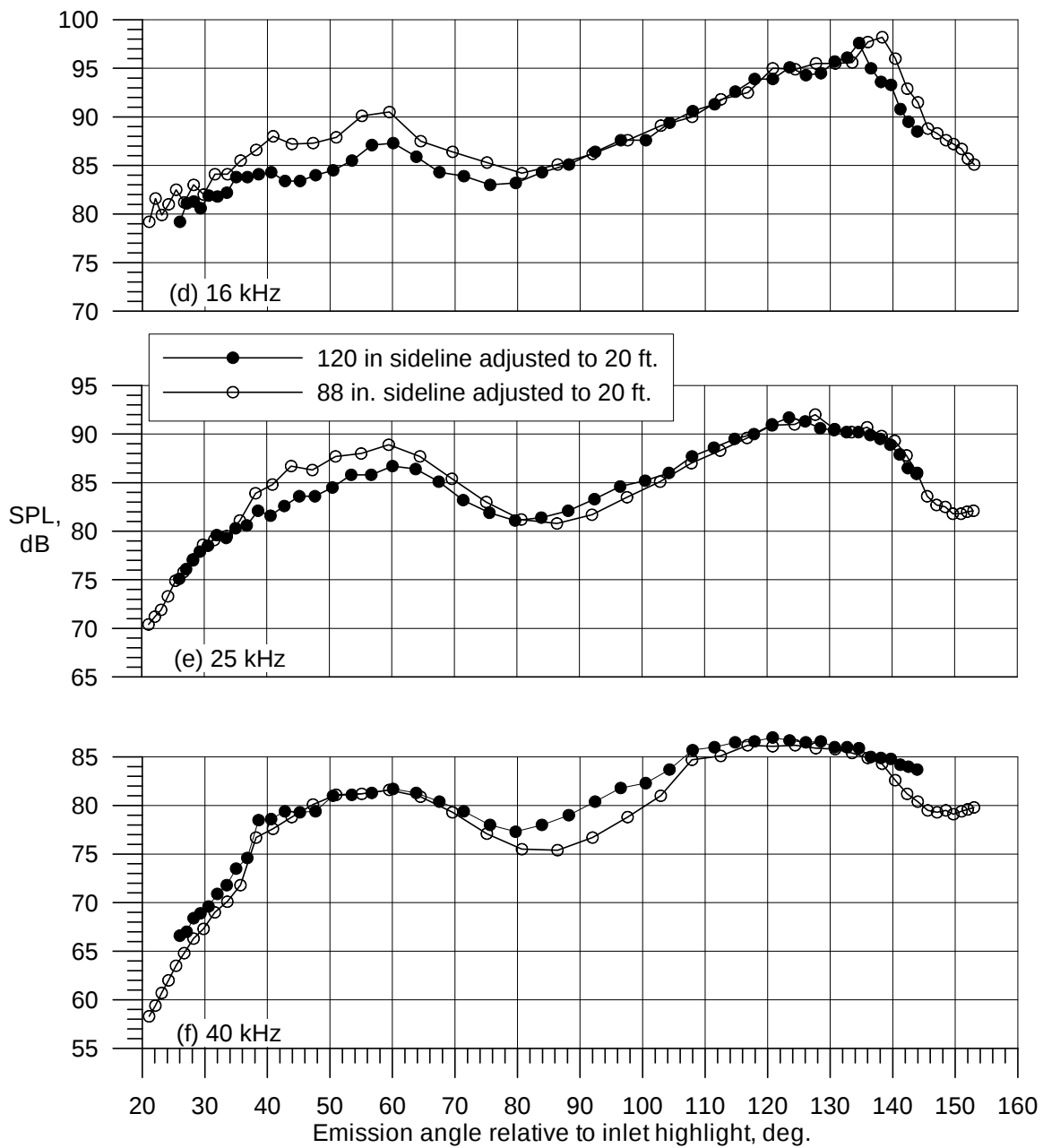


Figure 31.—Concluded.

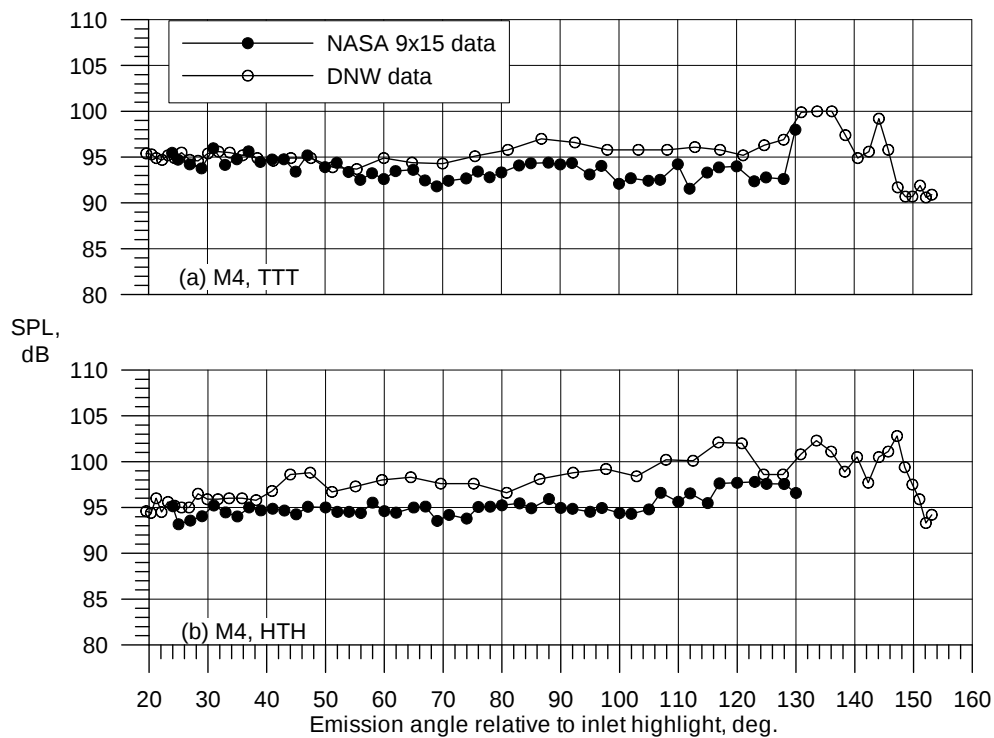


Figure 32.—Comparison of UPS data acquired in the NASA 9x15 LSWT and within the free jet of the DNW free-jet facility. Both data were acquired with the NASA streamlined microphone holder on a nominal 88 in. sideline (8.1 k rpm_c, 1/3rd directivities at 6.3 kHz (contains bypass 2BPF and core BPF tones), Mach number 0.20).

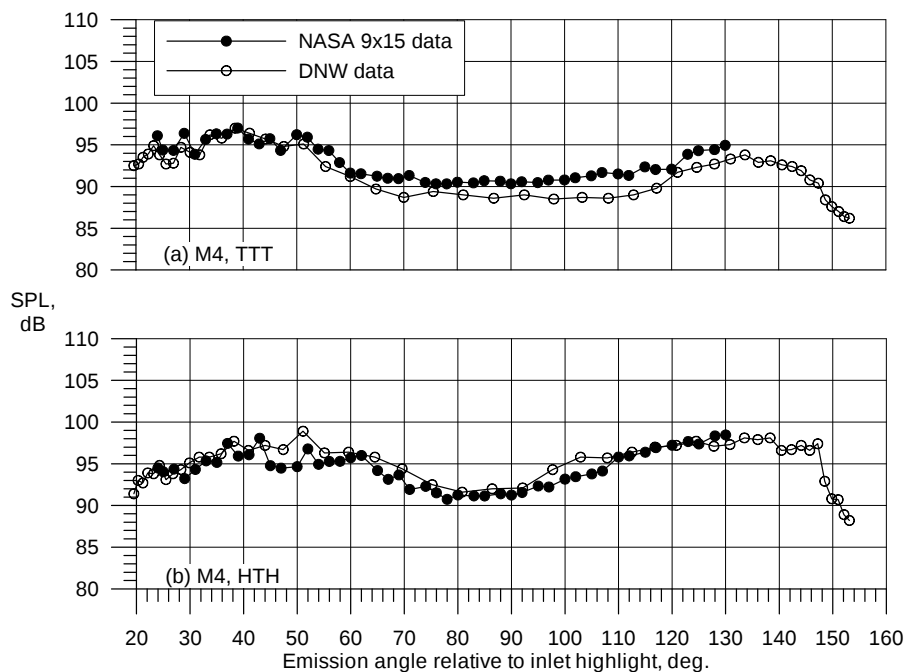


Figure 33.—Comparison of UPS data acquired in the NASA 9x15 LSWT and within the free jet of the DNW freejet facility. Both data were acquired with the NASA streamlined microphone holder on a nominal 88-in. sideline (8.1 k rpm_c, 1/3rd directivities at 10 kHz (broadband spectral region), Mach number 0.20).

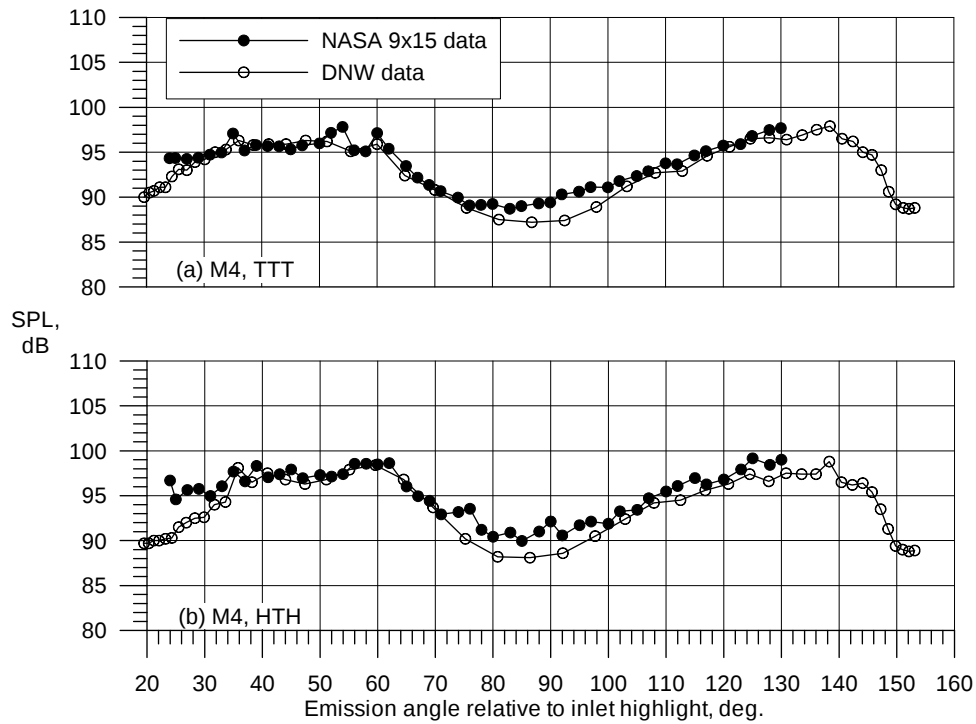


Figure 34.—Comparison of UPS data acquired in the NASA 9x15 LSWT and within the free jet of the DNW free-jet facility. Both data were acquired with the NASA streamlined microphone holder on a nominal 88-in. sideline (8.1 k rpm_c, 1/3rd directivities at 20 kHz (broadband spectral region), Mach number 0.20).

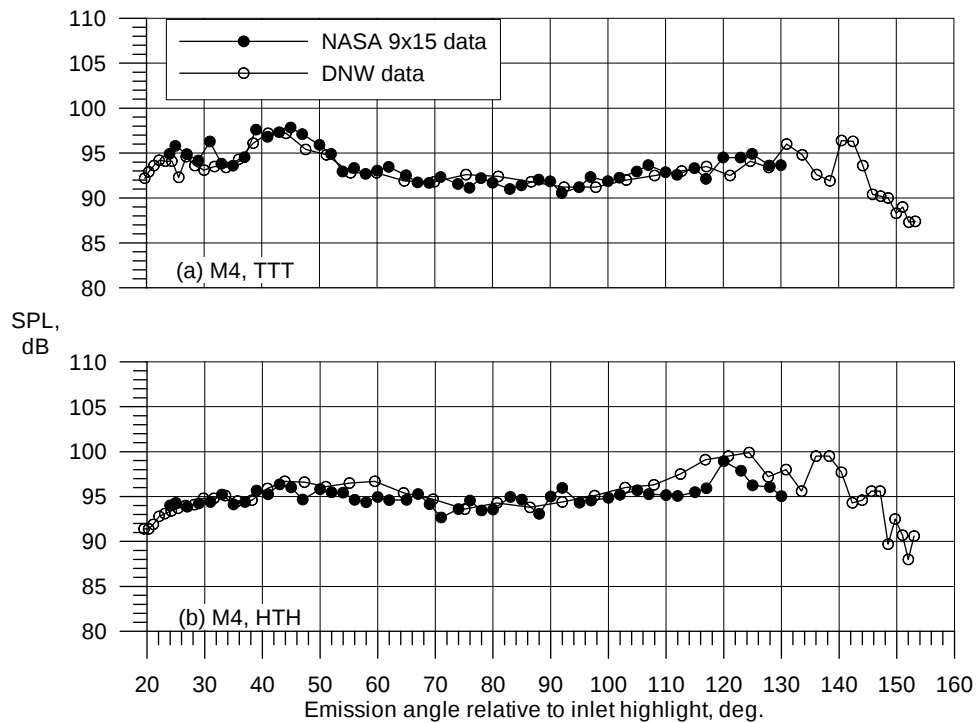


Figure 35.—Comparison of UPS data acquired in the NASA 9x15 LSWT and within the free jet of the DNW free-jet facility. Both data were acquired with the NASA streamlined microphone holder on a nominal 88-in. sideline (10 k rpm_c, 1/3rd directivities at 4 kHz (broadband spectral region), Mach number 0.20).

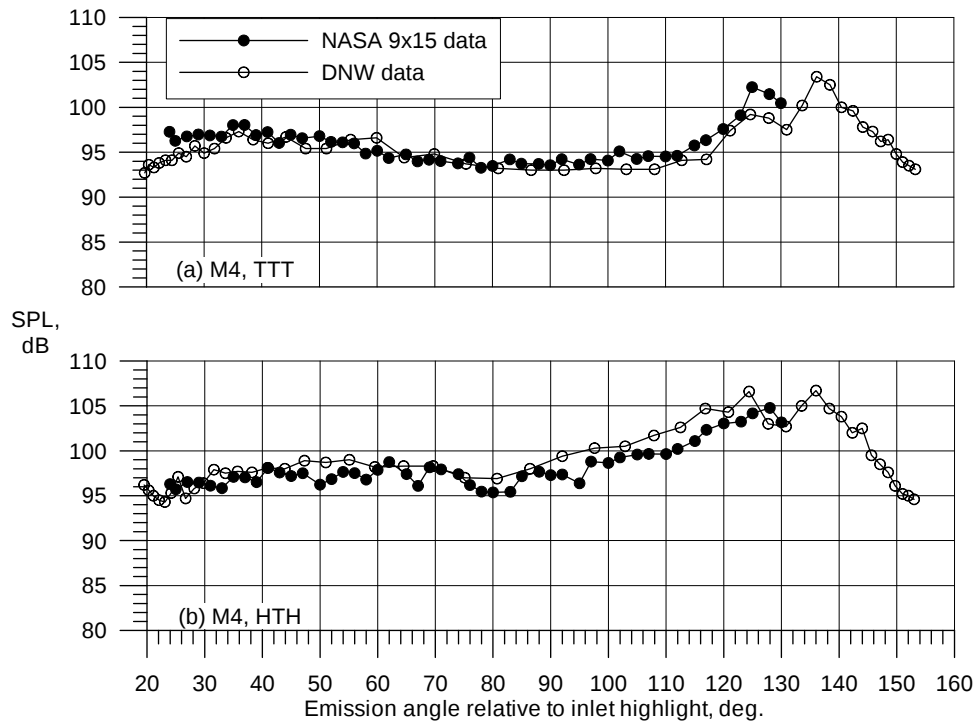


Figure 36.—Comparison of UPS data acquired in the NASA 9x15 LSWT and within the free jet of the DNW free-jet facility. Both data were acquired with the NASA streamlined microphone holder on a nominal 88-in. sideline (10 k rpm_c, 1/3rd directivities at 8 kHz (contains bypass 2BPF and core BPF tones), Mach number 0.20).

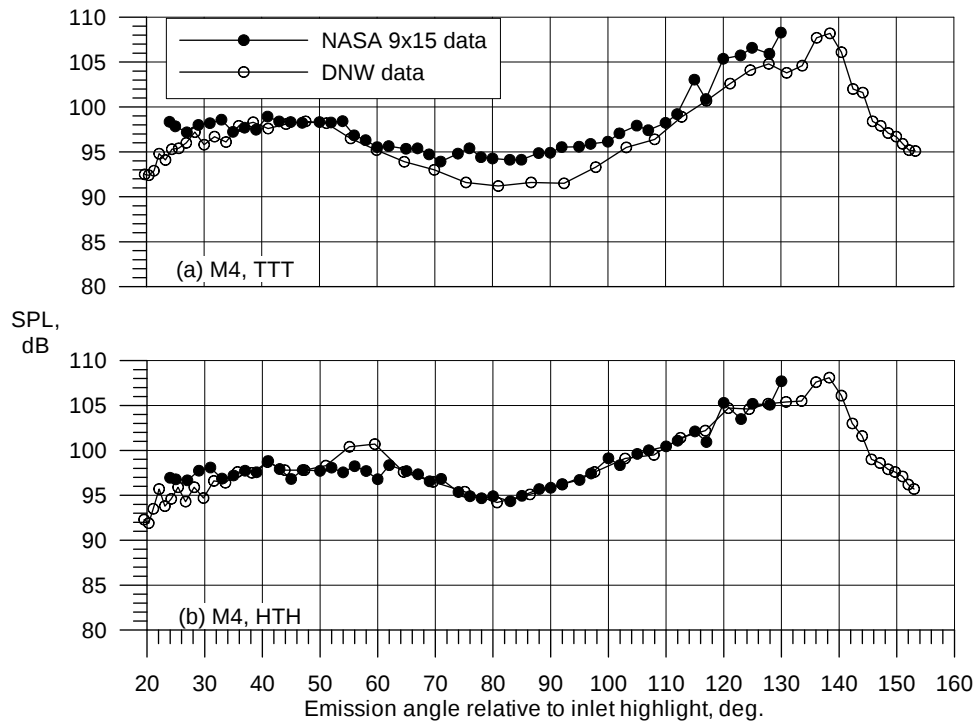


Figure 37.—Comparison of UPS data acquired in the NASA 9x15 LSWT and within the free jet of the DNW free-jet facility. Both data were acquired with the NASA streamlined microphone holder on a nominal 88-in. sideline (10 k rpm_c, 1/3rd directivities at 16 kHz (contains bypass 4BPF and core 2BPF tones), Mach number 0.20).

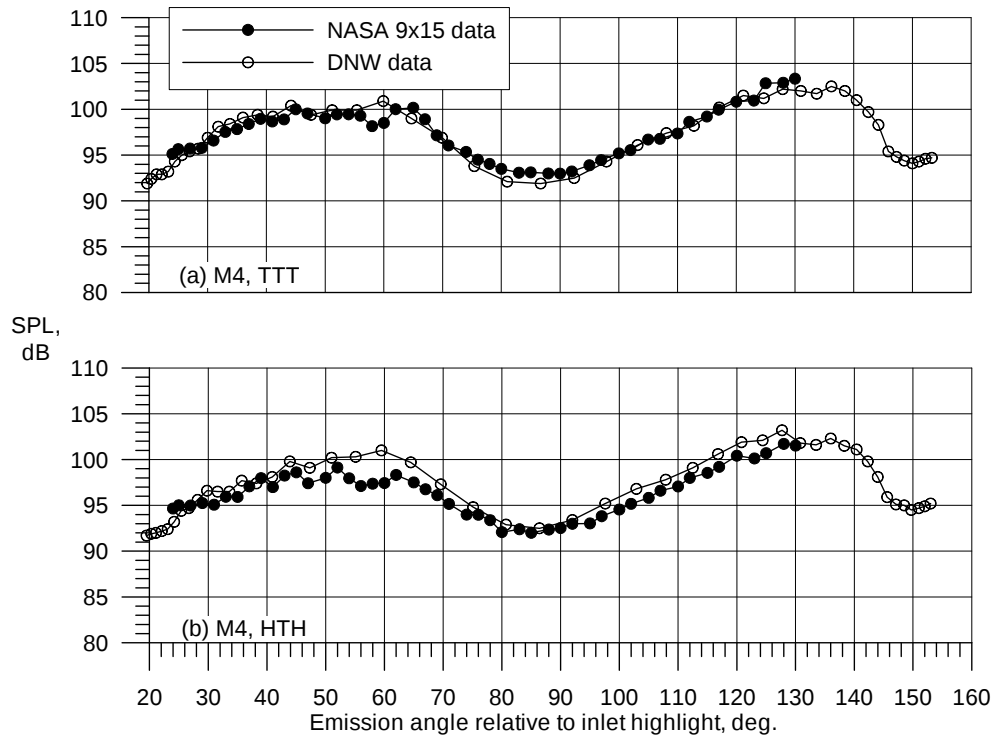


Figure 38.—Comparison of UPS data acquired in the NASA 9x15 LSWT and within the free jet of the DNW free-jet facility. Both data were acquired with the NASA streamlined microphone holder on a nominal 88-in. sideline (10 k rpm_c, 1/3rd directivities at 25 kHz (contains bypass 6BPF and core 3BPF tones), Mach number 0.20).

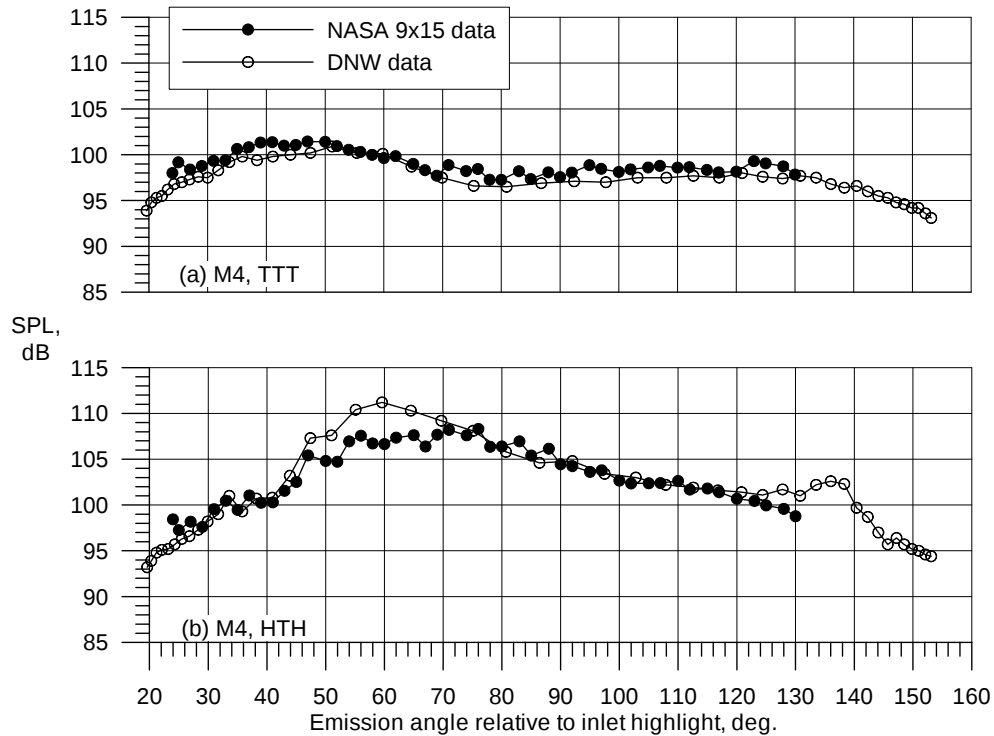


Figure 39.—Comparison of UPS data acquired in the NASA 9x15 LSWT and within the free jet of the DNW free-jet facility. Both data were acquired with the NASA streamlined microphone holder on a nominal 88-in. sideline (12 k rpm_c, 1/3rd directivities at 4 kHz (broadband spectral region), Mach number 0.20).

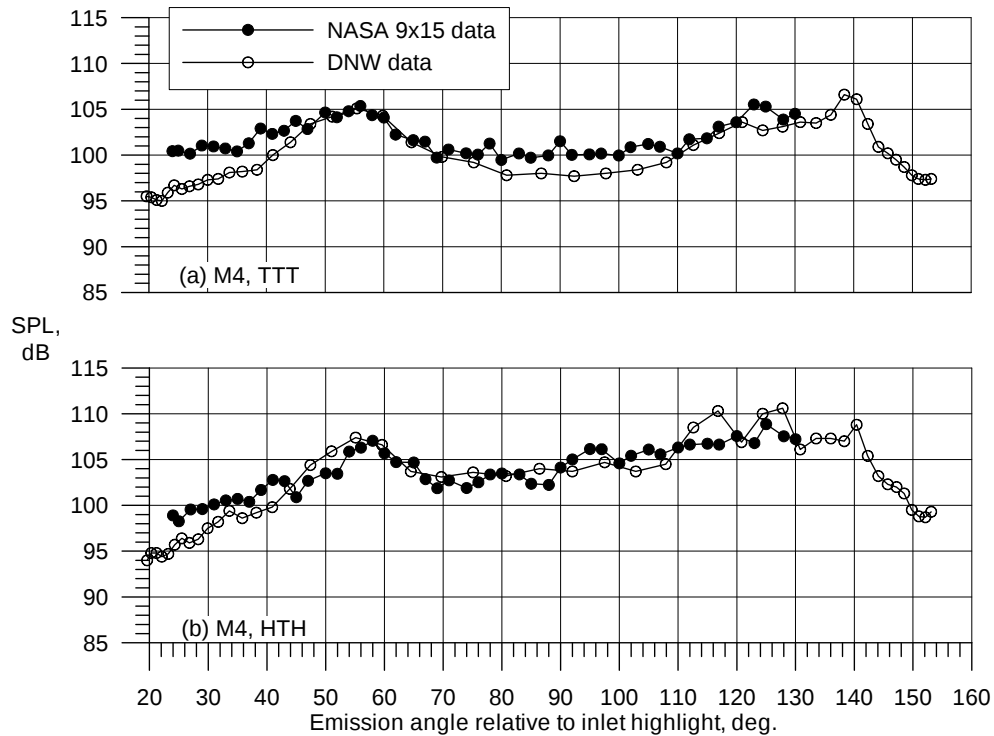


Figure 40.—Comparison of UPS data acquired in the NASA 9x15 LSWT and within the free jet of the DNW free-jet facility. Both data were acquired with the NASA streamlined microphone holder on a nominal 88-in. sideline (12 k rpm_c, 1/3rd directivities at 10 kHz (contains bypass 2BPF and core BPF tones), Mach number 0.20).

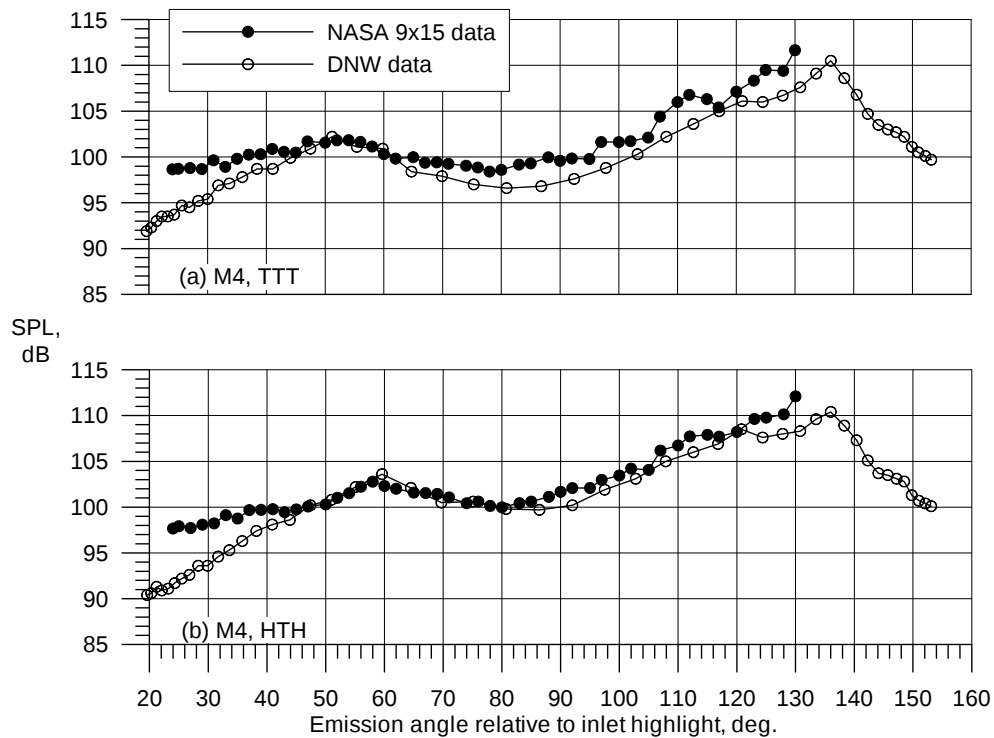


Figure 41.—Comparison of UPS data acquired in the NASA 9x15 LSWT and within the free jet of the DNW free-jet facility. Both data were acquired with the NASA streamlined microphone holder on a nominal 88-in. sideline (12 k rpm_c, 1/3rd directivities at 20 kHz (contains bypass 4BPF and core 2BPF tones), Mach number 0.20).

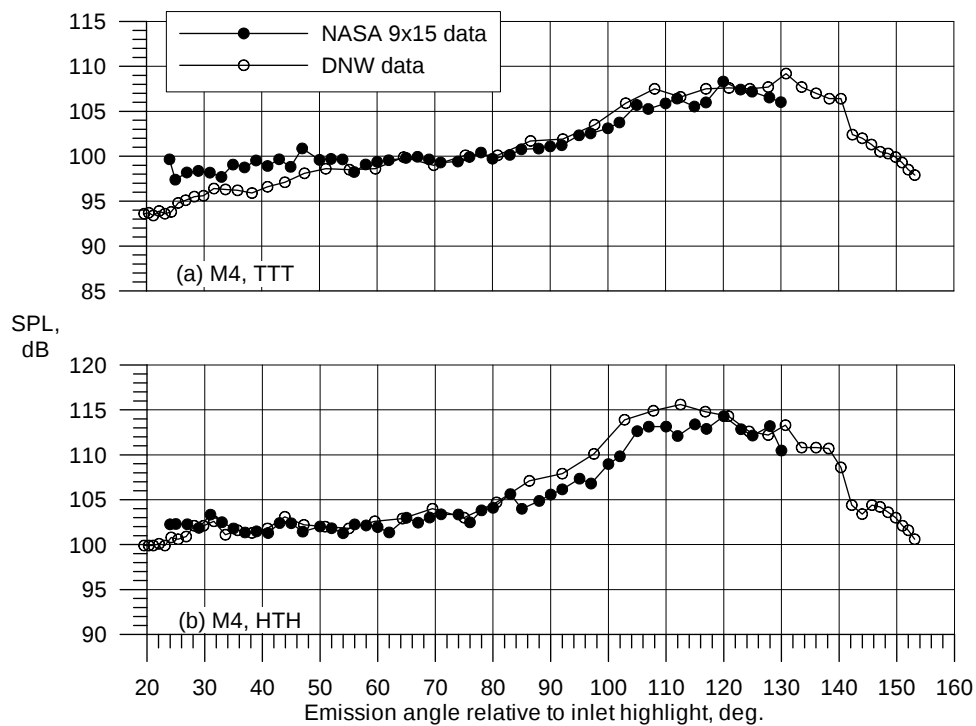


Figure 42.—Comparison of UPS data acquired in the NASA 9×15 LSWT and within the free jet of the DNW free-jet facility. Both data were acquired with the NASA streamlined microphone holder on a nominal 88-in. sideline (13.5 k rpm_c, 1/3rd directivities at 5 kHz (contains bypass BPF tone), Mach number 0.20).

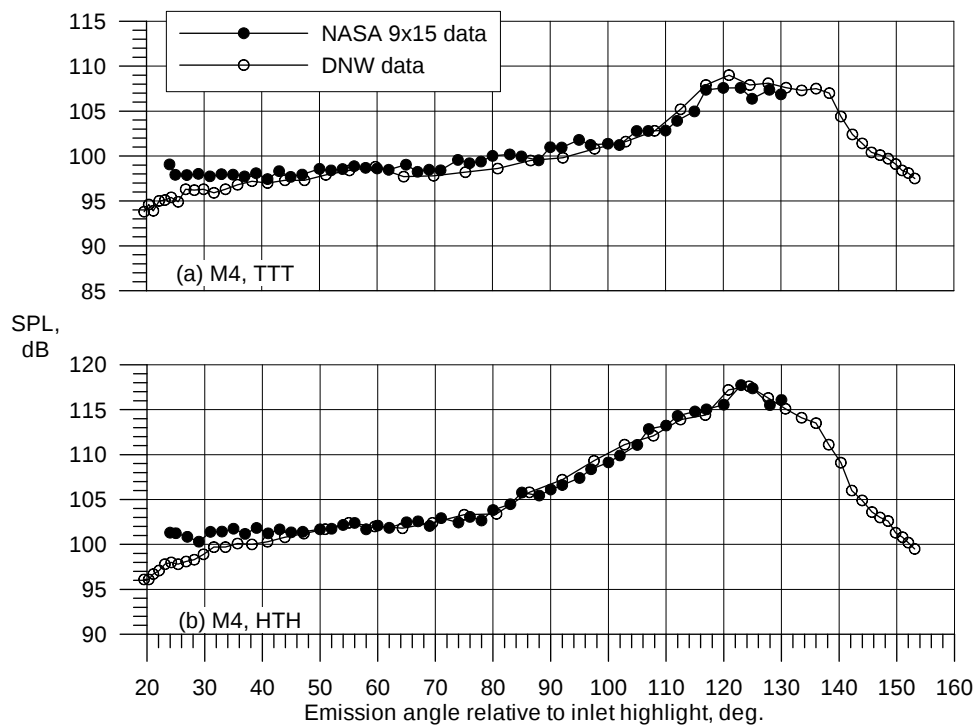


Figure 43.—Comparison of UPS data acquired in the NASA 9×15 LSWT and within the free jet of the DNW free-jet facility. Both data were acquired with the NASA streamlined microphone holder on a nominal 88-in. sideline (13.5 k rpm_c, 1/3rd directivities at 8 kHz (broadband spectral region), Mach number 0.20).

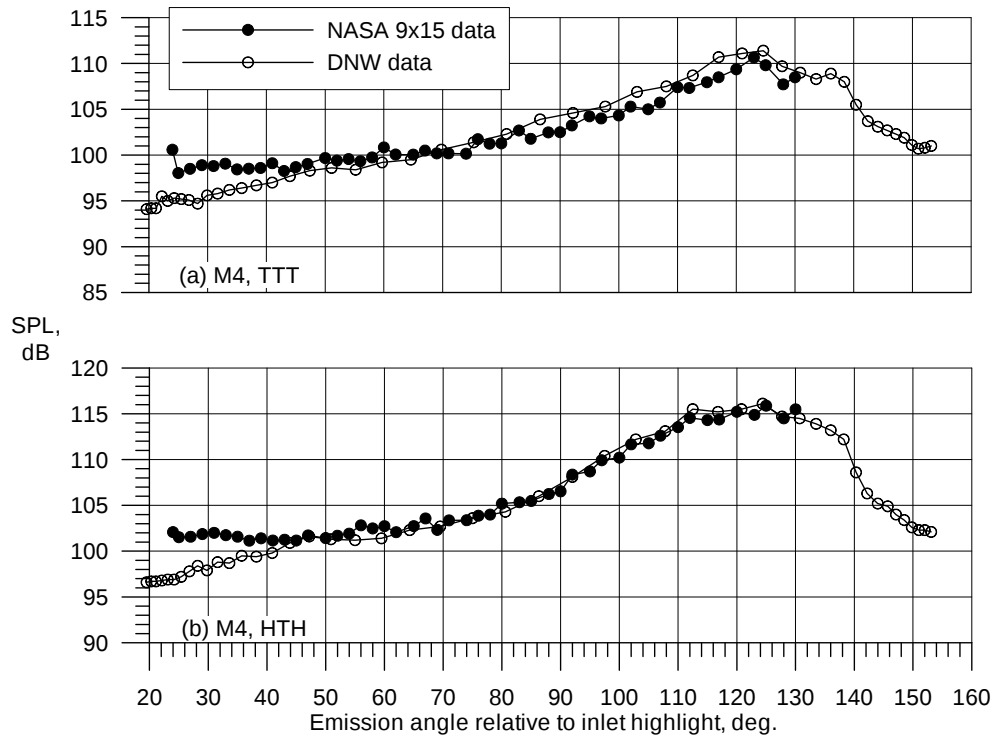


Figure 44.—Comparison of UPS data acquired in the NASA 9×15 LSWT and within the free jet of the DNW free-jet facility. Both data were acquired with the NASA streamlined microphone holder on a nominal 88-in. sideline (13.5 k rpm_c, 1/3rd directivities at 10 kHz (contains bypass 2BPF and core BPF tones), Mach number 0.20).

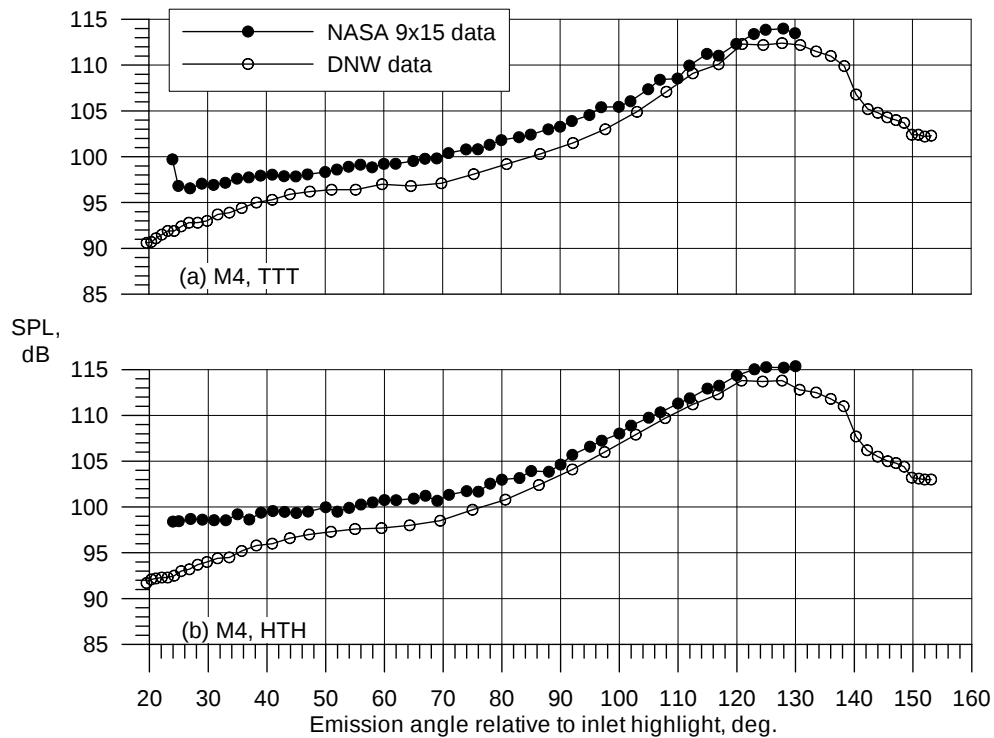


Figure 45.—Comparison of UPS data acquired in the NASA 9×15 LSWT and within the free jet of the DNW free-jet facility. Both data were acquired with the NASA streamlined microphone holder on a nominal 88-in. sideline (13.5 k rpm_c, 1/3rd directivities at 20 kHz (contains bypass 4BPF and core 2BPF tones), Mach number 0.20).

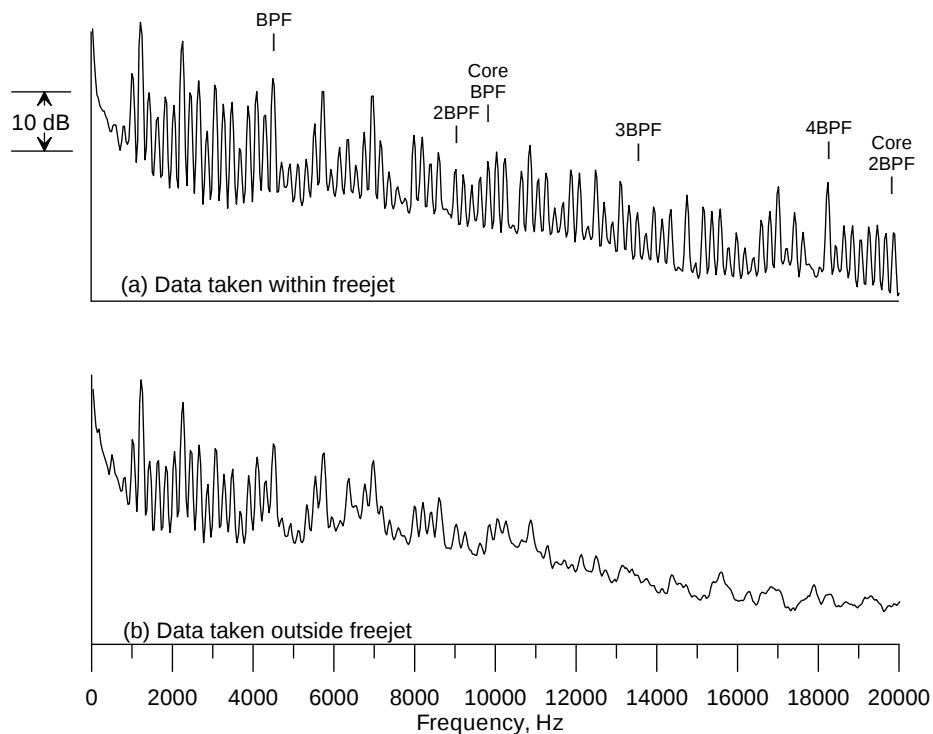


Figure 46.—Comparison of constant bandwidth (36 Hz) spectra acquired in the DNW facility within a Mach number 0.20 free jet and outside the freejet showing tone diffraction through the free jet shear layer. (12 k rpm_c, 60° emission angle, HTH).

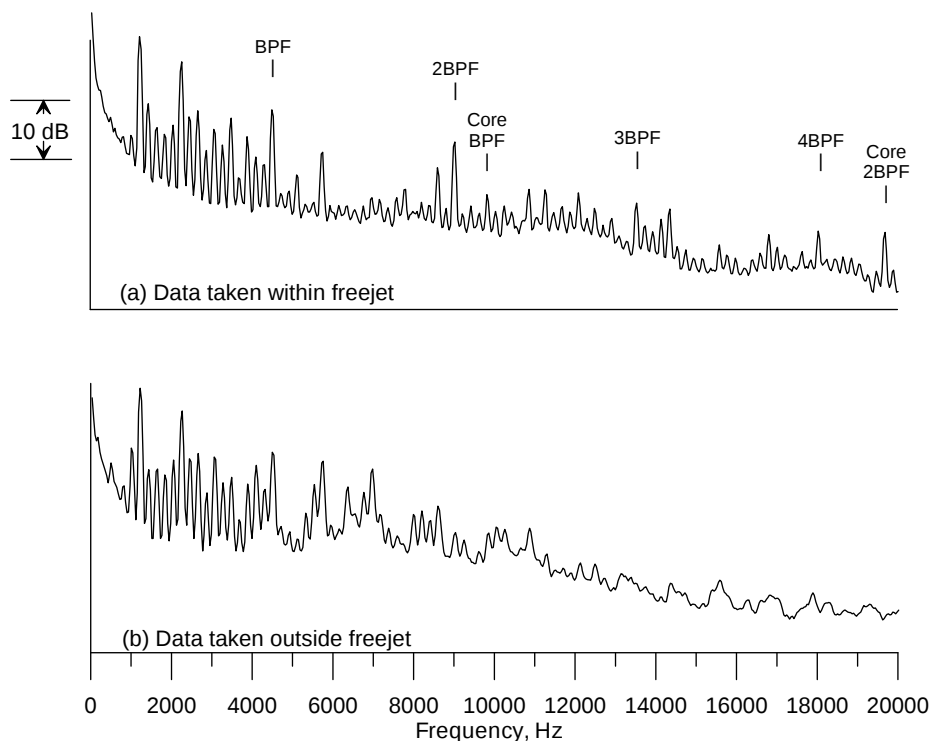


Figure 47.—Comparison of constant bandwidth (36 Hz) spectra acquired in the DNW facility within a Mach number 0.20 free jet and outside the free jet showing tone diffraction through the free-jet shear layer. (12 k rpm_c, 90° emission angle, HTH).

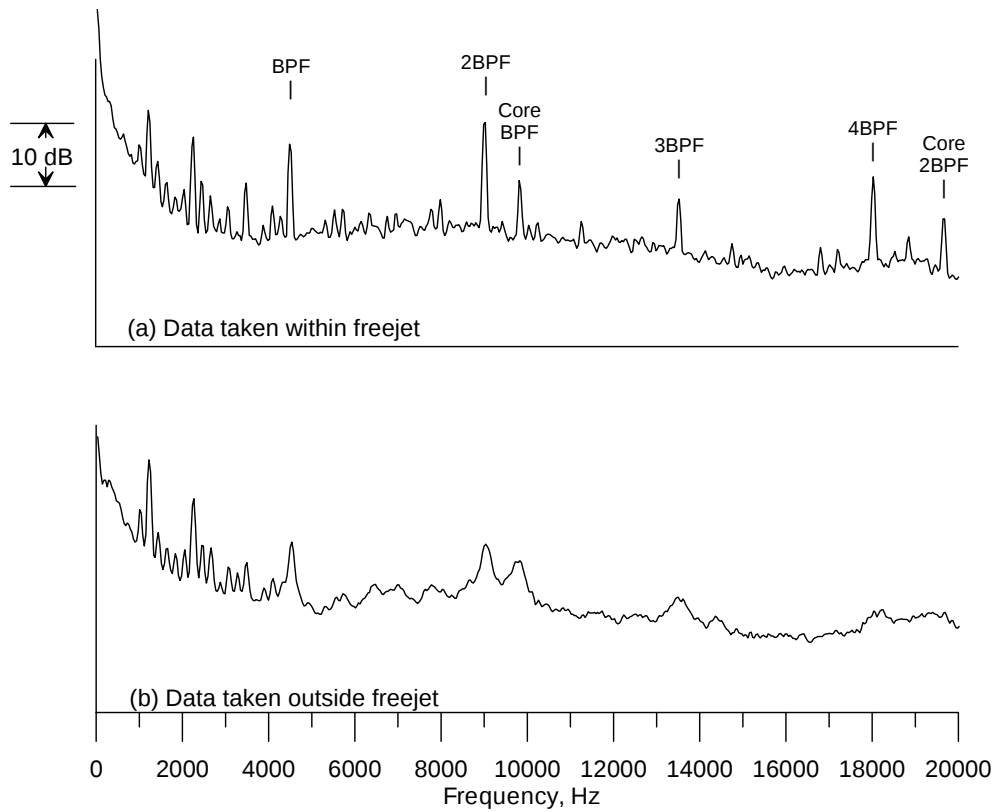


Figure 48.—Comparison of constant bandwidth (36 Hz) spectra acquired in the DNW facility within a Mach number 0.20 free jet and outside the free jet showing tone diffraction through the free jet shear layer. (12 k rpm_c, 120° emission angle, HTH).

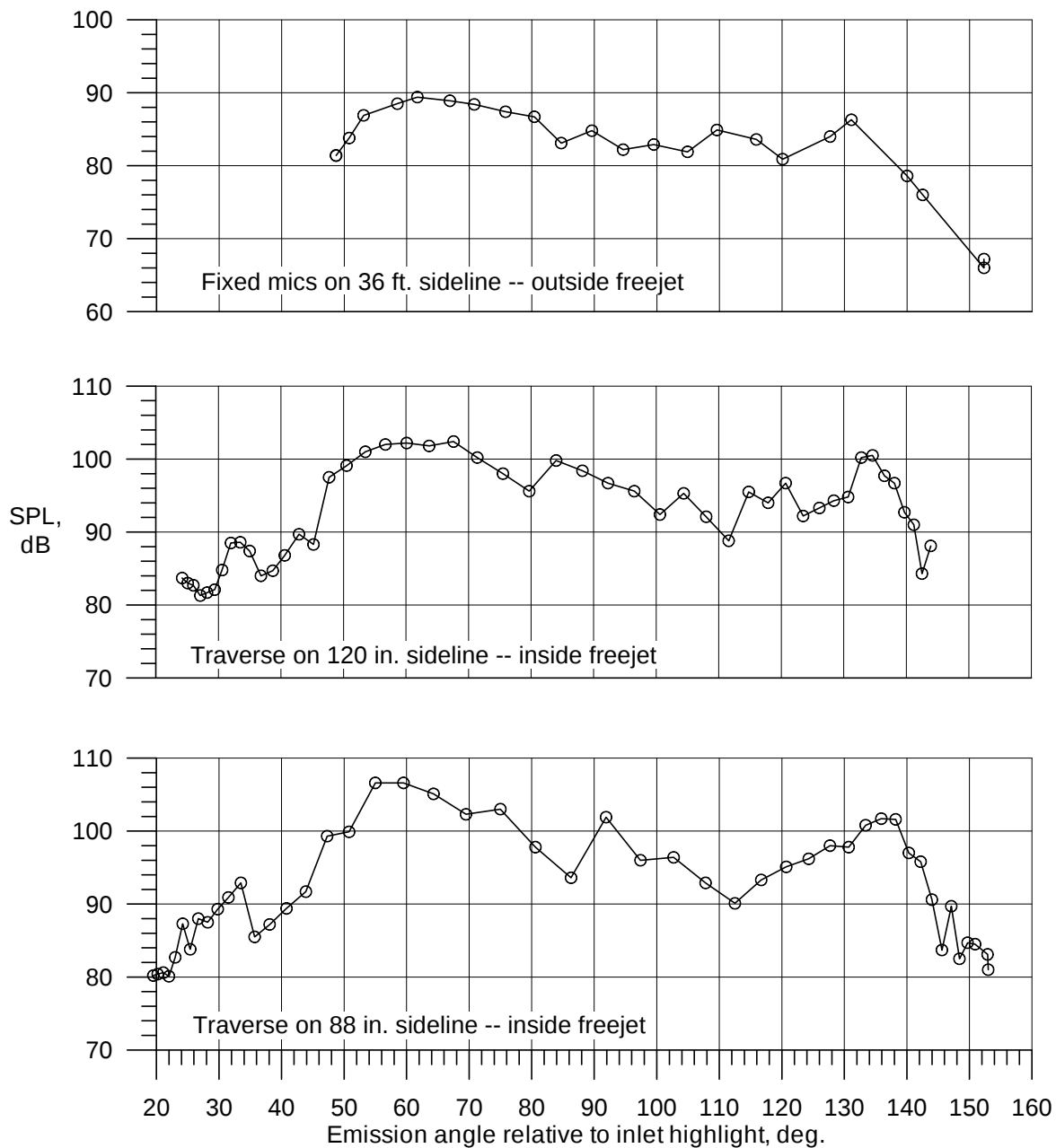


Figure 49.—Comparison of constant bandwidth (36 Hz) directivities acquired in the DNW facility within a Mach number 0.20 free jet and outside the freejet showing tone diffraction through the free jet shear layer (12 k rpm_c, bypass BPF tone, M4, HTH).

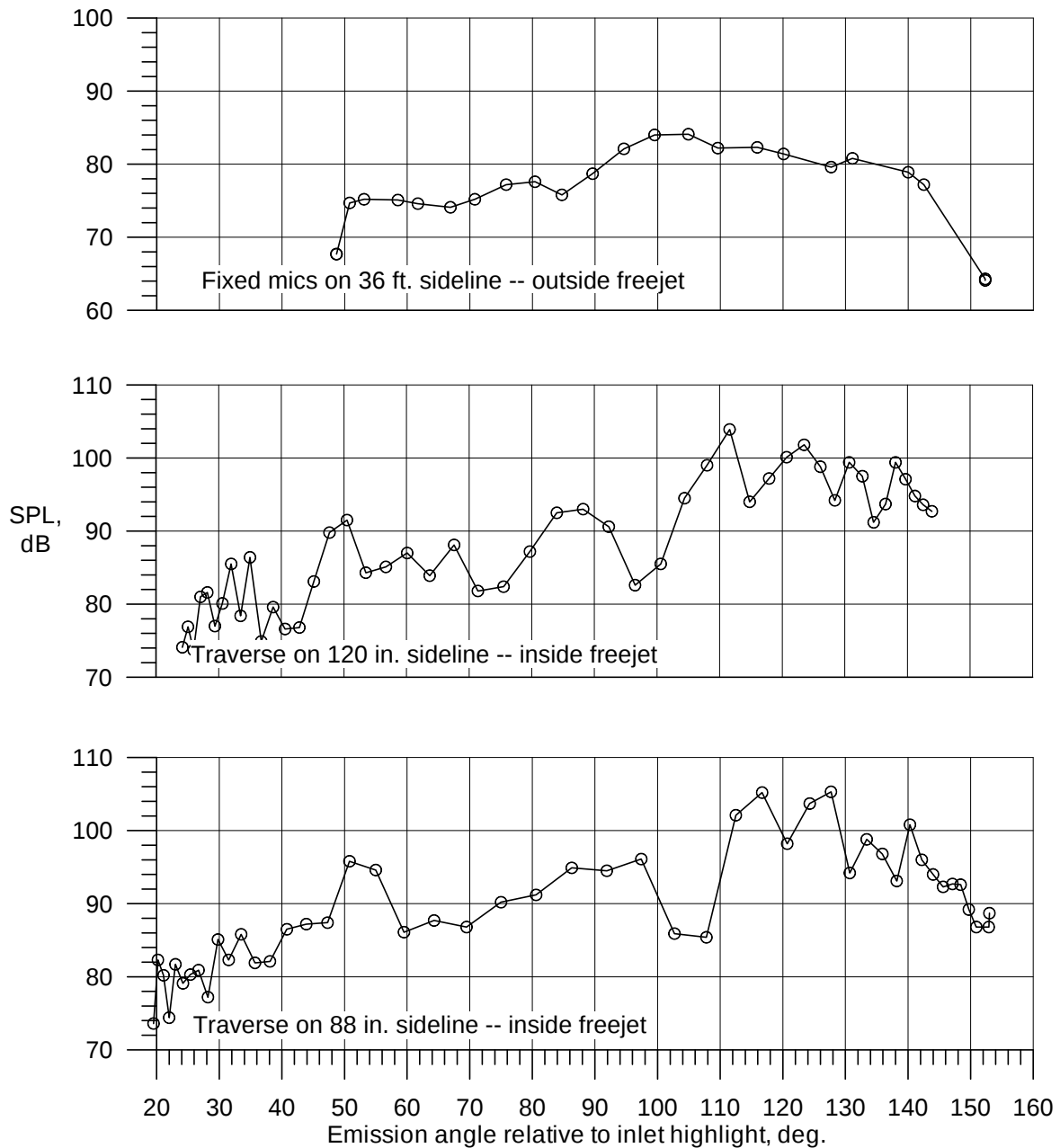


Figure 50.—Comparison of constant bandwidth (36 Hz) directivities acquired in the DNW facility within a Mach number 0.20 free jet and outside the free jet showing tone diffraction through the free jet shear layer (12 k rpm_c, bypass 2BPF tone, M4, HTH).

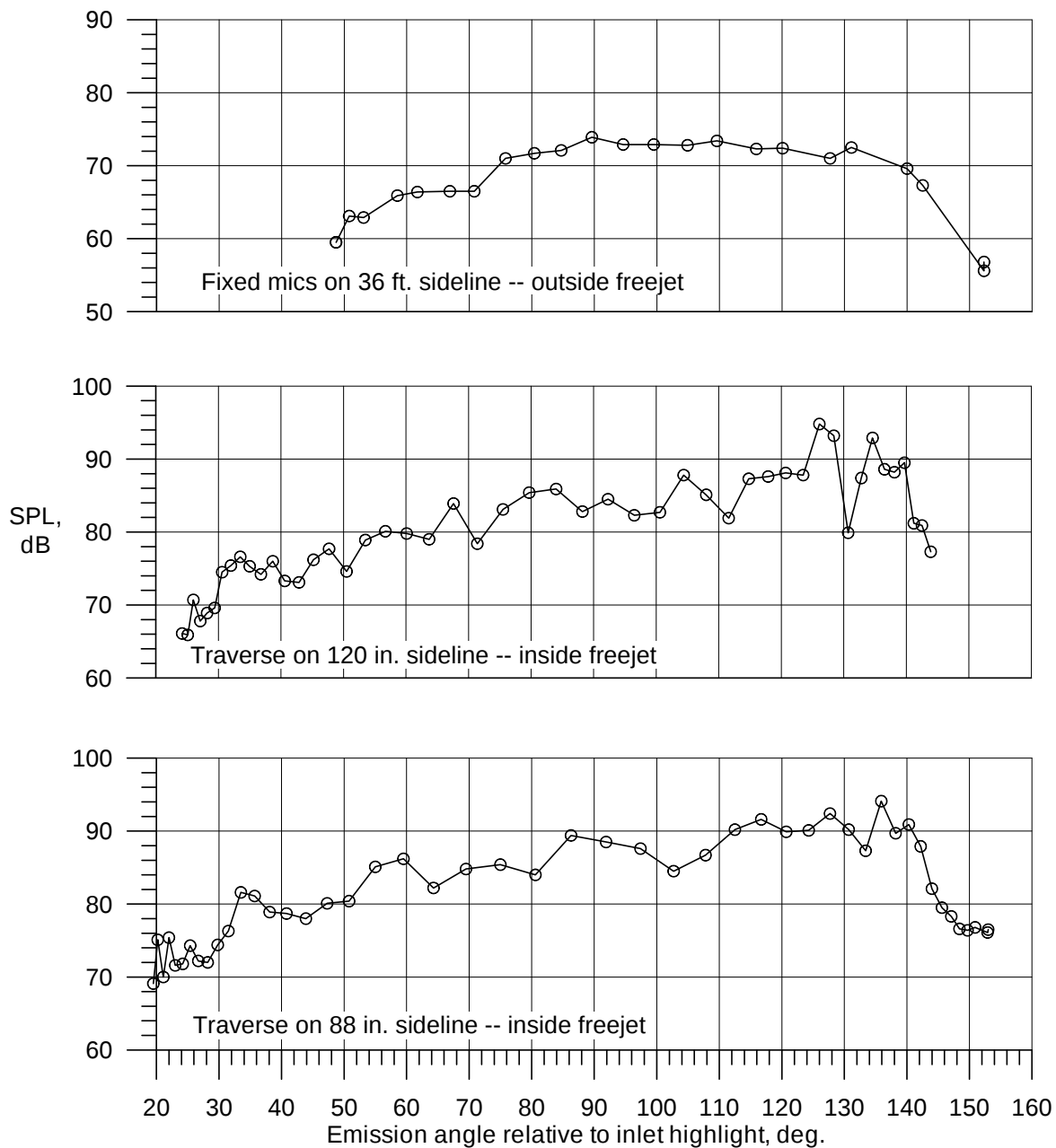


Figure 51.—Comparison of constant bandwidth (36 Hz) directivities acquired in the DNW facility within a Mach number 0.20 free jet and outside the free jet showing tone diffraction through the free jet shear layer (12 k rpm_c, bypass 3BPF tone, M4, HTH).

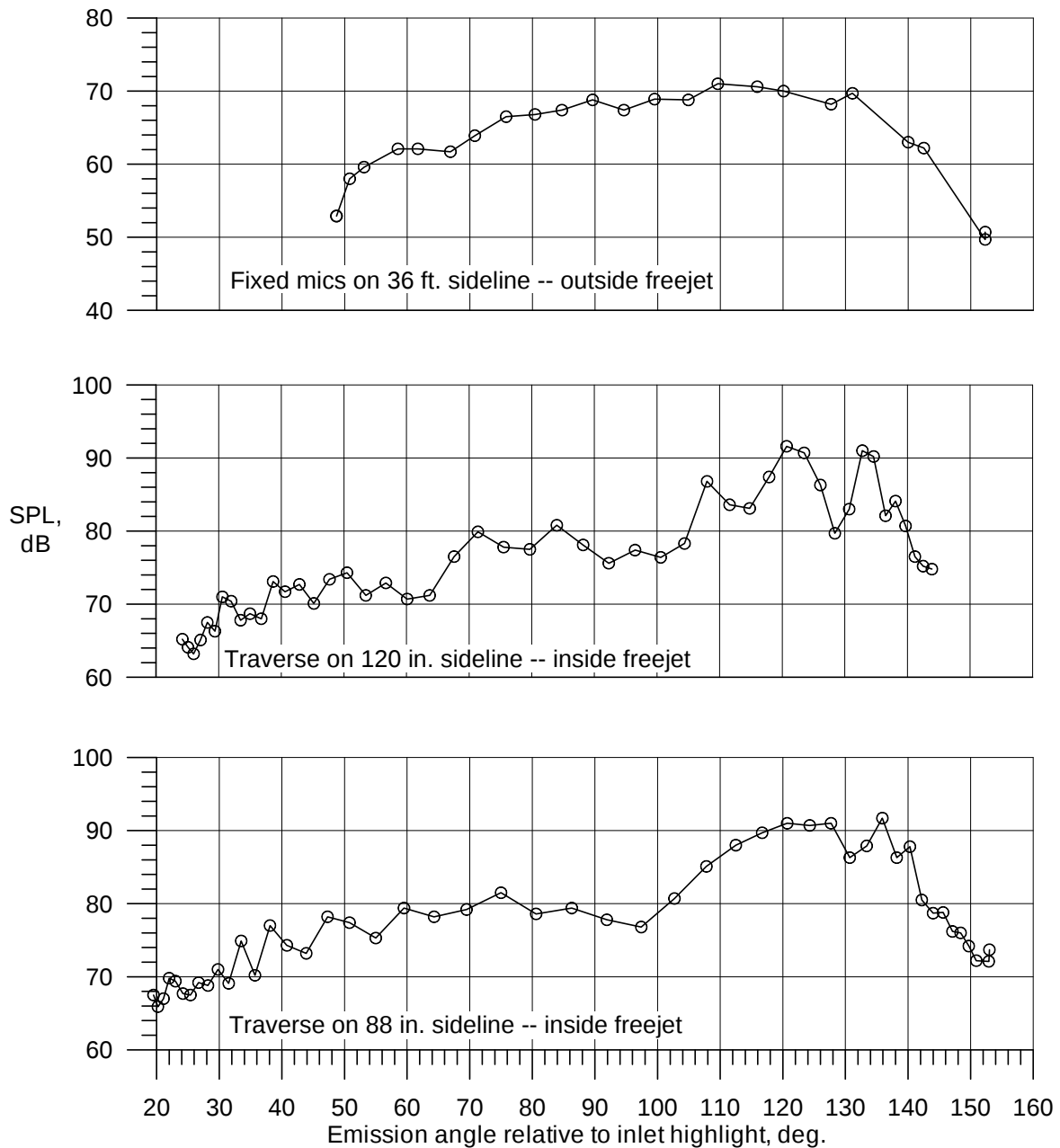


Figure 52.—Comparison of constant bandwidth (36 Hz) directivities acquired in the DNW facility within a Mach number 0.20 free jet and outside the free jet showing tone diffraction through the free jet shear layer (12 k rpm_c, bypass 4BPF tone, M4, HTH).

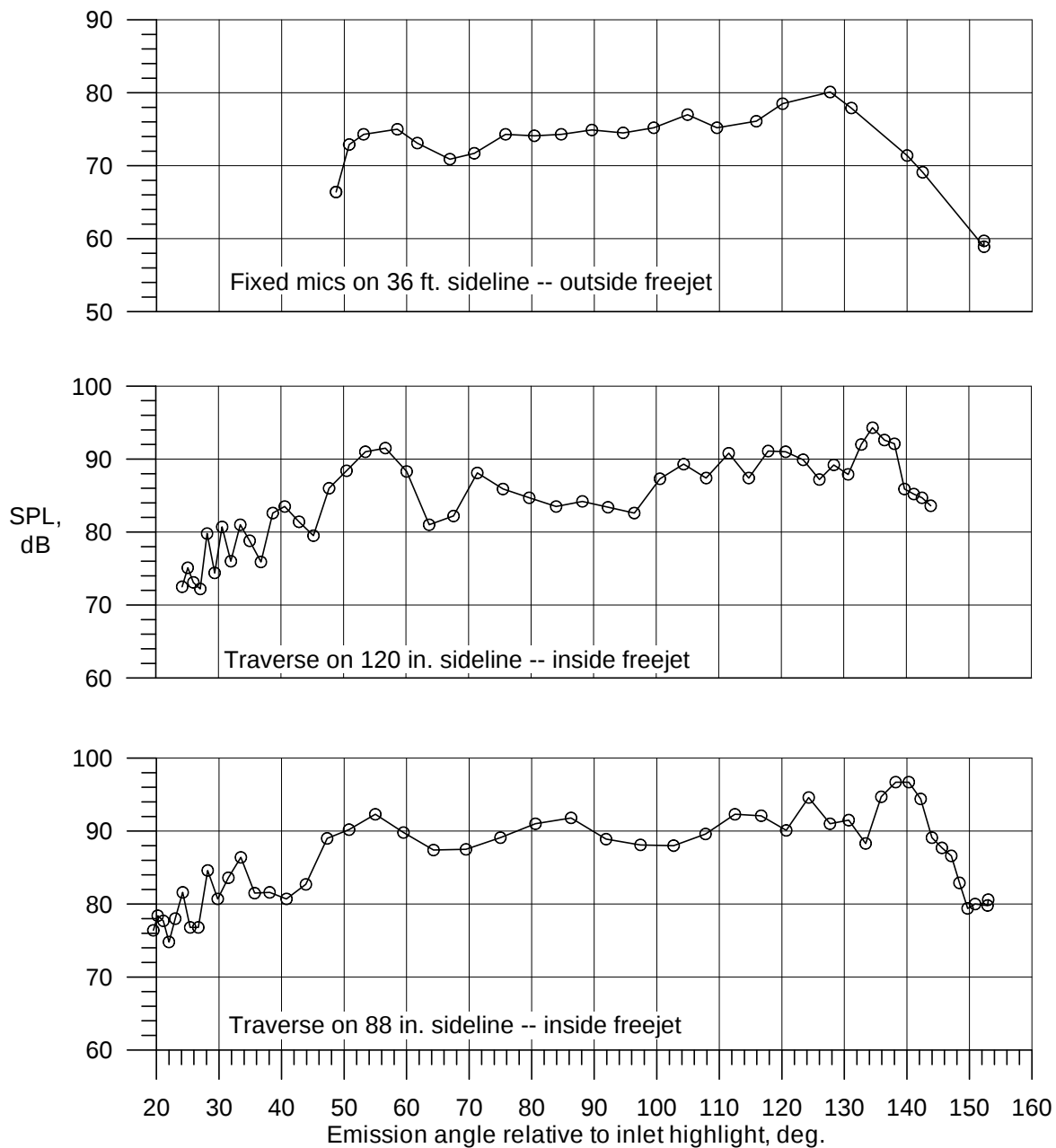


Figure 53.—Comparison of constant bandwidth (36 Hz) directivities acquired in the DNW facility within a Mach number 0.20 free jet and outside the free jet showing tone diffraction through the free jet shear layer (12 k rpm_c, core BPF tone, M4, HTH).

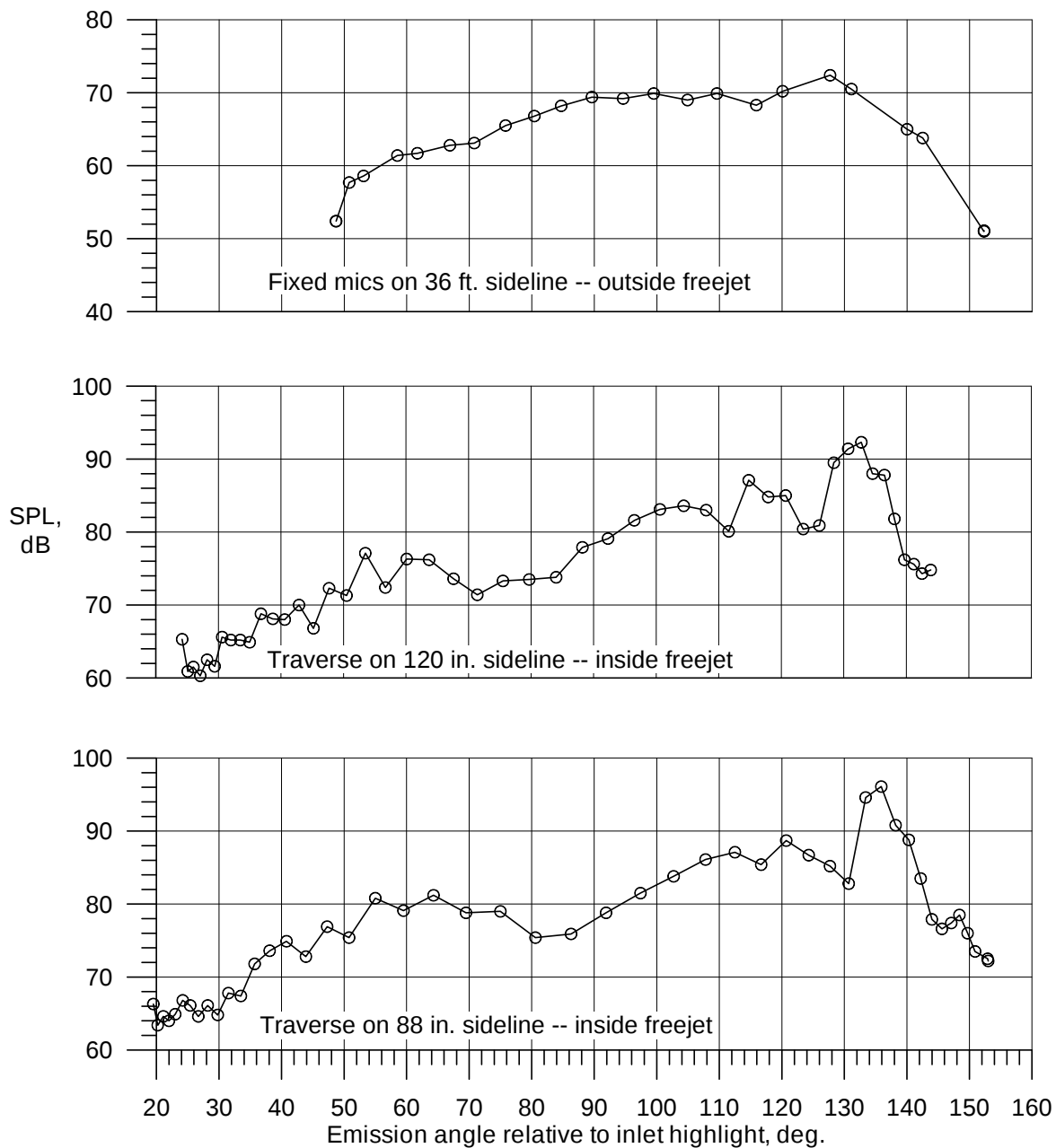


Figure 54.—Comparison of constant bandwidth (36 Hz) directivities acquired in the DNW facility within a Mach number 0.20 free jet and outside the free jet showing tone diffraction through the free jet shear layer (12 k rpm_c, core 2BPF tone, M4, HTH).

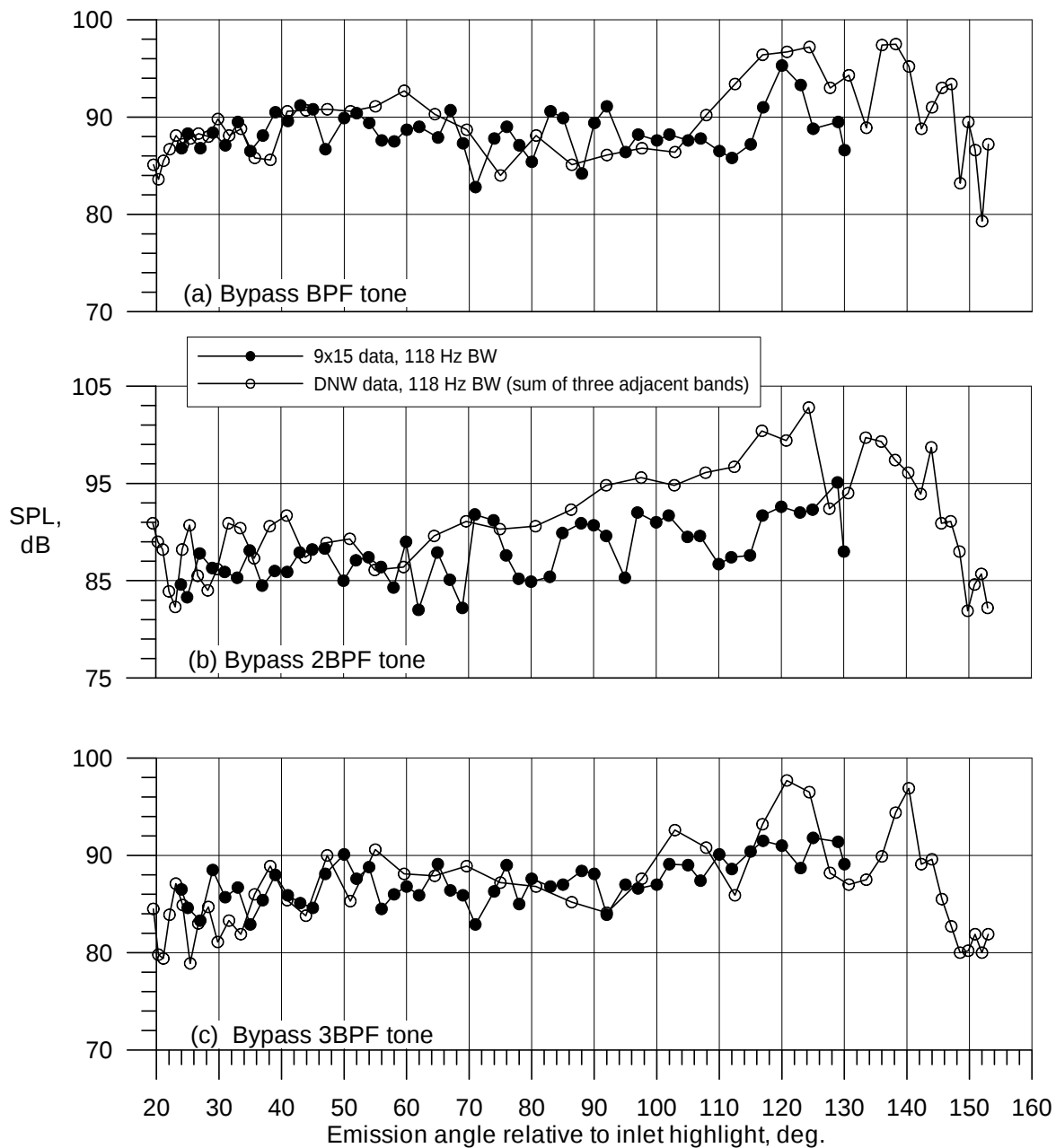


Figure 55.—Comparison of “in-flow” constant bandwidth directivities acquired in the DNW and in the NASA 9×15 LSWT on a nominal 88-in. sideline (10 k rpm_c, 0.20 M, M4, HTH).

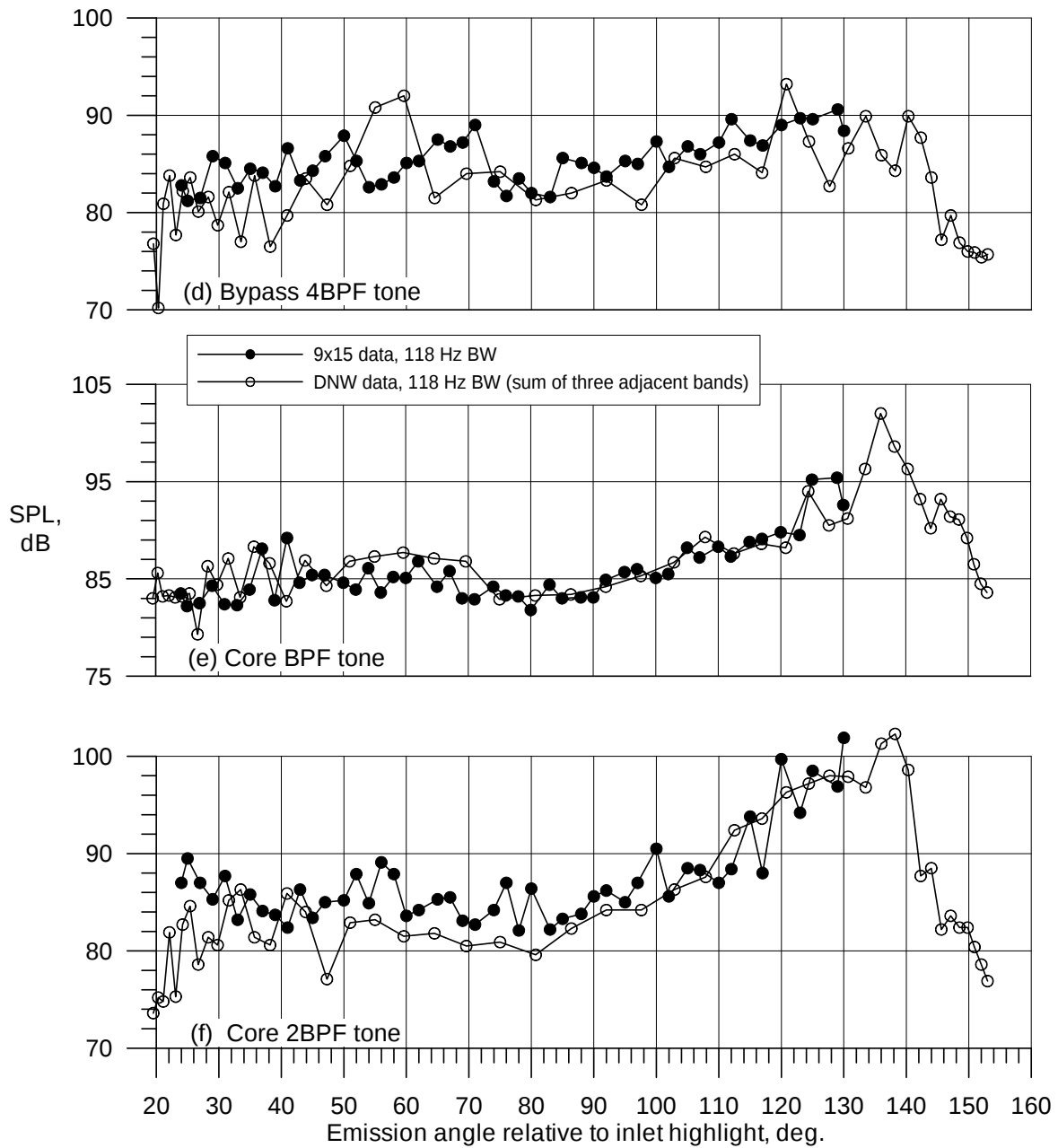


Figure 55.—Concluded.

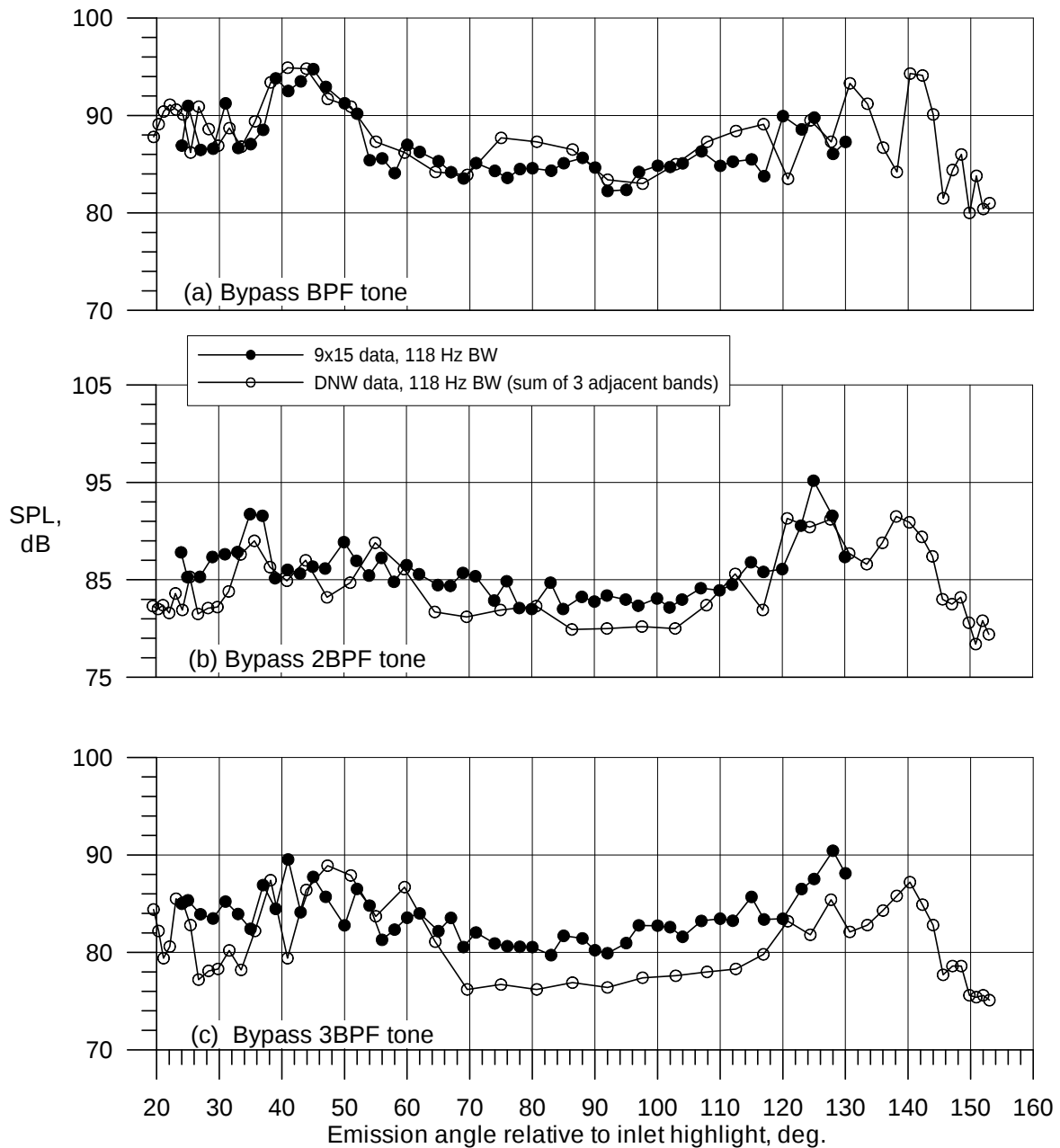


Figure 56.—Comparison of “in-flow” constant bandwidth directivities acquired in the DNW and in the NASA 9×15 LSWT on a nominal 88-in. sideline (10 k rpm_c, Mach number 0.20, M4, TTT).

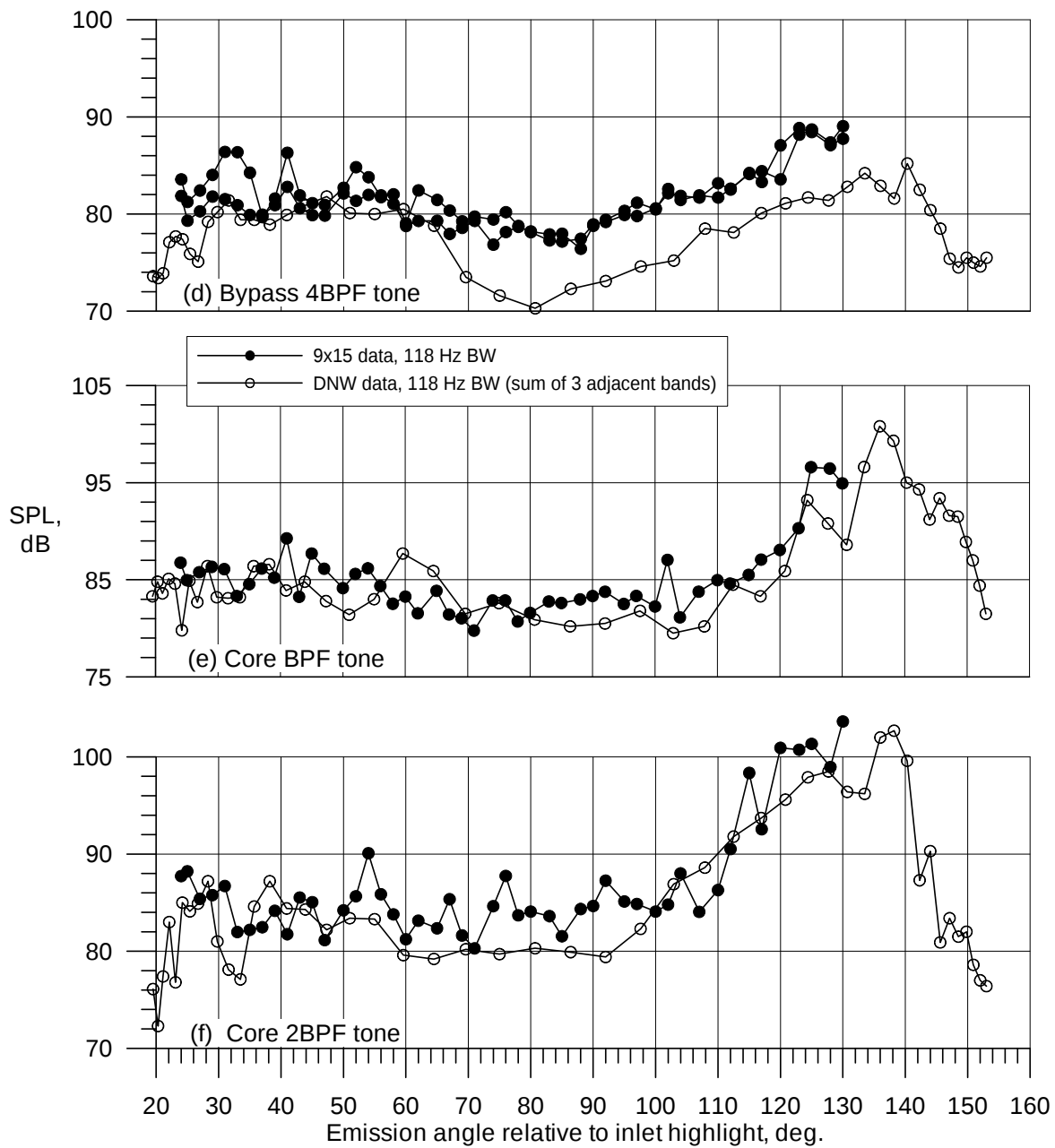


Figure 56.—Concluded.

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14. ABSTRACT A model advanced turbofan was acoustically tested in the NASA Glenn 9- by 15-Foot-Low-Speed Wind Tunnel (LSWT), and in two other aeroacoustic facilities. The Universal Propulsion Simulator (UPS) fan was designed and manufactured by the General Electric Aircraft Engines (GEAE) Company, and featured active core, as well as bypass, flow paths. The reference test configurations were with the metal, M4, rotor with hardwall and treated bypass flow ducts. The UPS fan was tested within an airflow at a Mach number of 0.20 (limited flow data were also acquired at a Mach number of 0.25) which is representative of aircraft takeoff and approach conditions. Comparisons were made between data acquired within the airflow (9×15 LSWT and German-Dutch Wind Tunnel (DNW)) and outside of a free jet (Boeing Low Speed Aero acoustic Facility (LSAF) and DNW). Sideline data were acquired on an 89-in. (nominal 4 fan diameters) sideline using the same microphone assembly and holder in the 9×15 LSWT and DNW facilities. These data showed good agreement for similar UPS operating conditions and configurations. Distortion of fan spectra tonal content through a free jet shear layer was documented, suggesting that in-flow acoustic measurements are required for comprehensive fan noise diagnostics. However, there was good agreement for overall sound power level (PWL) fan noise measurements made both within and outside of the test facility airflow.					
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